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TECHNICAL MEMORANDUM

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UTTER OF A HEAT SHIELD PANEL

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from: C. C. Ong

subject: Flutter of a Heat Shield Panel
Case 237

TECHNICAL MEMORANDUM

1.0 INTRODUCTION

It has been well established that the design of the thermal protection system (TPS) is one of the most critical technology areas in the development of a reusable Space Shuttle. It is also generally recognized that for thin-sheet metallic radiative heat shields, panel flutter may be a design problem for which further investigations are needed.

Panel flutter is important because, as a design criterion, it may significantly affect the TPS structural weight. Since the feasibility and the long term economy of a reusable Space Shuttle is very sensitive to the structural weight of which a substantial portion will be associated with the TPS, it is imperative to explore all possible means to reduce weight in structural design. An understanding of the flutter problem and its relative importance to other parameters in the design process would greatly facilitate the choice of materials and structural configurations. It may also have a profound effect on the selection of basic design concepts by answering such a question as whether a metallic thin sheet is an efficient design concept for the Space Shuttle heat shield from the panel flutter point of view.

The purposes of this memorandum are to present a general appreciation of the panel flutter problem, to assess its possible impact on the design of TPS, and to identify future investigations of value to the Space Shuttle program. The effects of various parameters on flutter behavior of a thin panel are discussed through a review of recent theoretical and experimental studies. Emphasis is placed on those factors which may have a significant impact on the structural design of a heat shield panel. Discussions are limited to panels subjected to supersonic flow, which is generally believed to be the flow range important to panel flutter.

2.0 PANEL FLUTTER

2.1 The Phenomenon of Panel Flutter

Flutter is an aeroelastic, self-excited vibration in which the airstream is the only source of external energy. When a thin plate is placed parallel to an airstream with air flowing over one side of the plate, a self-excited oscillation may occur over a range of critical dynamic pressure. This oscillation, caused by the interaction of aerodynamic forces, inertia characteristics, and elastic deformation is called panel flutter. The flutter amplitudes are usually limited by the nonlinear behavior of the in-plane stresses; thus, panel flutter is generally considered to be primarily a fatigue problem. However, catastrophic failure caused by panel flutter has occasionally been experienced.

2.2 Flight Experience with Panel Flutter

Panel flutter was first encountered in flight by the German V-2 missiles and came to be a well recognized type of dynamic instability by the early 1950's. However, during that time it was considered merely an academic problem of little practical significance. Its seriousness in structural design and the need for intensive research were not identified until the early flights of the X-15 hypersonic research plane in the late 1950's. Since then, several aircraft, while operating well into the supersonic regime, have experienced extreme noise levels, cracks in surface panels, and loss of panels, all of which were attributed to panel flutter.[1] Considerable flight data on panel flutter have been accumulated but only a few have been published, and many of these are in classified reports. In order to obtain some feeling on the flutter behavior of exposed skin panels, unclassified information on test flights of X-15 hypersonic airplane and aerothermoelastic vehicles used in the ASSET program (Aerothermodynamic/Elastic Structural System Environment Tests) are briefly discussed here.

2.2.1 X-15 Program[1,2]

The lightweight design of the X-15 resulted in some very thin skins which proved to be susceptable to panel flutter. During the early flights, some of the unstiffened and corrugation-stiffened Inconel-X panels suffered severe vibration attributed to flutter. These were the long-narrow, unstiffened rectangular panels of the vertical tail and corrugation stiffened panels of fuselage side fairings. The initial design of these panels was not influenced by panel flutter considerations. The skin panels of the vertical tail were unsupported over a length of about 60 inches with a rib spacing of about 6 inches. The side fairings that experienced flutter were rectangular panels sized from 12 by 15 inches to 23 by 34 inches and stiffened by corrugations across the flow direction. Flutter of side-fairings panels was detected at a dynamic pressure as low as 650 lb/sq ft and fatigue cracks were observed during post flight inspection.

Simple modification of the panels consisting of riveting J-section or hat-section stiffeners to the corrugations or the inner surface of the unstiffened skin at the center-line of the panel in the stream direction proved to be very effective in correcting the problem. Stiffeners in the traverse direction were also used as shown in Figure 1, but test results showed that they were ineffective unless firmly restrained against rotation about the line of attachment to the panel. With panels so modified, dynamic pressure as high as 1,600 lbs/sq ft was encountered in the remaining flights of the X-15 with no further evidence of panel flutter. The effect of structural modification on the dynamic response of a side fairing panel obtained from flight measurements is illustrated in Figure 2.

2.2.2 ASSET Program[3,4]

One of the ASSET flight experiments was an investigation of panel flutter. An experimental panel was installed at the bottom central surface of the test vehicle and served as a sensor of panel flutter during the lifting re-entry flight with speeds up to 13,000 fps. The 10 inch by 10 inch panel had to withstand a maximum design temperature of 2,200°F for a portion of the 11 minute glide re-entry while subjected to a maximum in-plane tension load of 165 pounds.

The panel design chosen consisted of a flat rectangular, single faced corrugation stiffened panel supported at two ends, free on the sides, and flush with the vehicle moldline. Tension between predetermined levels was applied longitudinally to the panel through the forward and aft supported edges during flight, thus making the panel alternately more or less susceptible to flutter. Figure 3 shows one of these single faced corrugation stiffened panels. The base sheet and the corrugation were made of 0.0045 inch columbium alloy foil protectively coated with LB-2 fused slurry alumnide. The actual flexing length between supports is 7.6 inches. Many flutter points (conditions) were identified in the flight test, indicating possible panel flutter under the ASSET flight environment. The numerical data from flight measurements are not presented here due to the classified nature of the information.

3.0 THEORETICAL CONSIDERATIONS

In formulating a panel flutter problem within the realm of continuum mechanics, it is not too difficult to write down the governing differential equation for a panel subjected to an aerodynamic pressure induced by the air flow over one side of the panel. But owing to the large number of parameters involved in a real structural problem, numerous simplifying assumptions are generally made to ensure solubility, numerical accuracy or to obtain a physical insight regarding a particular parameter, even for very simple structural configurations, edge construction and flow conditions. The results of analytical and associated experimental investigations indicate, however, that panel flutter is a very sensitive phenomenon which cannot be subjected to over simplification.

The panel flutter problem can be formulated on the basis of linear or nonlinear structural theory; in each case various aerodynamic theories can be applied to express the aerodynamic pressure as a forcing function. A majority of the earlier studies applied some form of linear structural theory and either steady or quasi-steady aerodynamic theory of nonviscous potential flow with idealized panel edge conditions, either simply supported or clamped. Only in the past few years have more complicated governing equations and boundary conditions been tackled. But at present there is still no reliable formulation with an accurate computing program that can be used to design against flutter for a panel of complex construction such as would be suitable for the heat shield of the Space Shuttle. In order to gain some insight into the problems involved, the theoretical considerations of the governing plate equation, the aerodynamic pressure, factors affecting the flutter behavior and techniques available to solve these boundary value problems are briefly discussed.

3.1 Governing Differential Equation

As mentioned earlier, both linear and nonlinear structural theories can be applied to the analysis of panel flutter. But so far most analytical studies are performed by using various forms of linear theory. For the purpose of illustration a typical linear differential equation for a rectangular orthotropic plate of homogeneous material can be written as:

$$L_S W + \rho \frac{\partial^2 W}{\partial t^2} - P = L_N W - L_G W - K_F W \qquad (1)$$

where

L_S = an operator describing all the nondissipative structural terms and, typically, takes the form of[5]

$$\frac{D_x}{1-\mu_x \mu_y} \frac{\partial^4}{\partial x^4} + 2\left(D_{xy} + \mu_x \frac{D_y}{1-\mu_x \mu_y}\right) \frac{\partial^4}{\partial x^2 \partial y^2} + \frac{D_y}{1-\mu_x \mu_y} \frac{\partial^4}{\partial y^4}$$

in which D_x, D_y, D_{xy} are flexural and twisting stiffnesses

μ_x, μ_y are Poisson's ratios

P = lateral pressure load due to air flow

L_N = an operator describing terms involving initial inplane loading, usually expressed as

$$N_x \frac{\partial^2}{\partial x^2} + 2N_{xy} \frac{\partial^2}{\partial x \partial y} + N_y \frac{\partial^2}{\partial y^2}$$

where Nx, Ny and Nxy are initial inplane forces

L_G = an operator describing all dissipative structural terms

K_F = stiffness of the elastic foundation

W = panel deflection

ρ = mass per unit area of panel

Depending on the particular problem investigated or the simplifying assumptions made, some or all of the terms on the right side of the equation may be omitted. Also, a set of edge conditions must be specified to completely formulate a boundary value problem. By using this equation for a thin panel, a rigid supporting substructure is assumed. Should the coupling effect between the heat shield panel and the substructure be considered, an additional differential equation for the motion of the substructure is needed. The coupled equations with appropriate boundary conditions would have to be solved to determine the flutter boundary (which signifies the onset of flutter) of the panel.

When a panel is made of nonhomogeneous anisotropic material such as a laminated plate with fiber-reinforced composite layers, the problem would be more complicated. For thin plates made of a small number of orthotropic laminae with unsymmetrical layer orientations, coupled differential equations taking into consideration the interaction between bending and stretching may be necessary to express the plate motion.[6]

It should be pointed out that nonlinear structural theories such as Von Karman's large deflection equations have been applied to analyze simple isotropic rectangular flat plates,[7] and more attention is being paid to nonlinear analysis than ever before.[8,9,10] In reality there are two important nonlinear mechanisms at work. One is the nonlinear interaction between the in-plane tensile stress and the transverse deformation, which keeps the deformation of a fluttering panel within the order of magnitude of the panel thickness. The other is the nonlinear aerodynamic pressure loading which may have a destabilizing effect.

3.2 Aerodynamic Pressure

When the flow direction is parallel to the plane of a flat panel, the aerodynamic pressure acting on the panel is induced primarily by the interaction of the panel deformation and the supersonic flow. The pressure load p in Equation (1) used by most investigators is derived from simplified linear aerodynamic theories. The two-dimensional static approximation of Ackeret Theory and the quasi-steady approximation or the so-called "Piston Theory" yield good results at Mach numbers greater than $\sqrt{2}$, but lead to erroneous flutter prediction when $M<\sqrt{2}$.[11] The quasi-steady approximation of aerodynamic pressure loading has been expressed as

$$p = \frac{2q}{\sqrt{M^2-1}} \frac{\partial w}{\partial x} + \frac{M^2-2}{M^2-1} \frac{1}{U} \frac{\partial w}{\partial t} \qquad (2)$$

where q = dynamic pressure

U = free stream air velocity

The first term is the primary aerodynamic force and the second term represents aerodynamic damping. This two-dimensional quasi-static expression assumes that the pressure on the bottom side remains at the free stream value, and it reduces to linear piston theory when the compressibility factor $\sqrt{M^2-1} \to M$ and the term $(M^2-2)/(m^2-1) \to 1$.

A static approximation can be obtained simply by dropping the second term of equation (2). The static approximation not only greatly simplifies the analysis but also, for a Mach number greater than 1.5, yields flutter boundaries for unstressed or uniformly stressed* isotropic panels in good agreement with experiments and with the results obtained by using three dimensional unsteady theory.[5,11] It has been the most frequently used expression for the aerodynamic pressure in formulating a panel flutter problem.

Very few past studies considered aerodynamic nonlinearity. In a recent publication[7] Eastep used the following expression from nonlinear piston theory for the pressure loading

$$p = \frac{2q}{M}\left\{\frac{\partial w}{\partial x} + \frac{1}{U}\ \frac{\partial w}{\partial t} + \frac{(\alpha_a+1)M}{4}\left[\left(\frac{\partial w}{\partial x}\right)^2 + \frac{2}{U}\frac{\partial w}{\partial x}\frac{\partial w}{\partial t}\right]\right\} \tag{3}$$

where α_a is a gas constant for air

In comparison with the linear piston approximation which can be deduced from Equation (2), this expression has two additional second-order terms. Eastep stated that the effect of the nonlinear term was to introduce a bias to the panel motion into the cavity. That is, the peak deflection into the flow is reduced while the peak deflection in the opposite direction is increased; but the overall effect was believed to be small.

3.3 Factors Influencing the Flutter Behavior of a Panel

Past analytical studies of simple, unstressed, isotropic flat plates yielded dynamic pressures for flutter in fair agreement with experiment for Mach number greater than about 1.4. However, for orthotropic or stressed panels, or panels with complex edge support condition, early theoretical results gave dynamic pressures for flutter quite different from experimental results, sometimes differing by several orders of magnitude. Recent investigations revealed that many factors, which had not been properly accounted for in formulating an analytical problem, could have profound influence on the flutter behavior of a panel. These factors include:

1. Edge and support conditions.

2. Thermally induced and mechanically applied in-plane loadings.

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*The static approximation is not accurate in the case where the stress level causes two modes of oscillation to have nearly the same frequency.

3. Panel configuration (orthotropicity, thickness, bending stiffnesses, transverse shear stiffness, torsional stiffness, and length-to-width-ratio).

4. Material properties.

5. Elastic coupling to substructures.

6. Pressure differential across the panel.

7. Damping characteristics.

8. Boundary layers.

9. Initial curvature.

10. Local flow condition (local Mach number and local dynamic pressure).

11. Flow angularity.

12. Angle of attack.

13. Cavity.

14. Initial imperfection.

15. Buckling.

The degree of success in an analysis depends to a great extent on the ability to properly incorporate some or all of these factors in the governing differential equation, such as equation (1) of section 3.1, and the associated boundary conditions for a particular case. Owing to the large number of parameters involved no one has succeeded in studying the flutter behavior of a panel with all these factors included in a single formulation. In order to formulate and solve the problem practically, it is essential to understand the effect and the relative importance of each factor. This will be discussed further later in this memorandum.

3.4 Methods of Analysis

Many techniques have been used for determining the onset of panel flutter from the governing equation discussed earlier or other direct energy methods. These techniques include exact method, normal mode analysis, Laplace transformation, integral equation, Lagrangian Multipliers, Galerkin's method, finite element and finite difference.[13,14] In general these methods can be grouped into analytical methods such as the first six listed and numerical methods like the last two. The capability of the former is limited, but usually approximate analytical solutions can be readily obtained for panels of simple construction. Galerkin's method has been the most frequently used technique in this category and Lagrangian Multipliers appear promising. For complex structures, solutions can be more easily obtained by numerical methods such as the matrix method based on discrete finite element idealization of the structure or a numerical solution of the differential equation by finite difference technique. In view of the likelihood of using complex panel configurations and edge support conditions, increased attention is being paid to numerical techniques. Therefore, only the Galerkin's method, the finite element and the finite difference techniques are briefly discussed here.

3.4.1 Galerkin's Method[13,15]

The method of modal expansion combined with Galerkin's procedure* has been the most widely used approximate method to date for the prediction of panel flutter. The method involves assuming a plate deflection function as a summation of terms, each the product of a function of time and a function of space. Then, Galerkin's procedure is applied to the governing equation to formulate an eigenvalue problem from which the dynamic instability signifying the onset of flutter is determined. The functions of space must satisfy the geometric boundary conditions, i.e., boundary conditions which specify slope and deflection of the plate. The force boundary conditions, i.e., those specifying moment and stress, should, but not necessarily, be satisfied by the assumed functions. This method is a powerful tool for solving flutter problems of isotropic panels with simple boundary conditions and a length-to-width ratio close to unity. For such geometry, flutter mode shape can be approximated with sufficient accuracy by a few assumed modes. When the length-to-width ratio of the plate is very large or when the plate is an orthotropic construction, a large number of assumed modes may have to be used for convergence, thus greatly increasing the computational effort.

There has been some doubt about the convergence of the Galerkin method. However, despite the frequent warnings from several investigators, there has been no case wherein the results obtained by Galerkin's approach actually failed to converge, although for certain cases of complex geometry the convergence may be extremely slow. But care must be exercised in applying this technique, particularly when two

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A commonly used approximate method in structural dynamics in which the weighted averages of the error over a structural domain are assumed to be zero.

coupled differential equations with more than one dependent variable are involved, which might be the case for a plate made of inhomogeneous anisotropic material or when the coupling between a heat shield panel and the substructure caused by an elastic insulation system is taken into consideration. In such cases, one of the practices is to first uncouple the equations and then apply the Galerkin's method to a single equation involving only one of the dependent variables. Such a practice has been considered mathematically unsound and may lead to large errors.[16] It is also questionable whether Galerkin's technique can be applied to panels with complex boundary conditions which are likely to be used for Space Shuttle heat shield panels.

Since Galerkin's expansion generally requires fewer degrees of freedom and, therefore, less computer time than either finite difference or finite element approach, it is believed that for relatively simple configurations and boundary conditions this method is still a practical one. It should also be noted that the capability of this method will be greatly enlarged if experimentally determined vibrational modal patterns are available which can accurately represent deflectional modes used in the analysis.

3.4.2 Finite Element

The finite element method is a mathematical modeling technique using a set of idealized discrete elements to simulate an actual continuous structure. The formulation of the problem is accomplished essentially by equating energies of the continuous and the discrete-element systems. The solutions tend to approach the exact values of the continuous system as the size of discrete elements is reduced. Rapid progress in developing finite element technique has been made in the past decade, and it is becoming one of the most powerful mathematical tools in the field of structural mechanics.

Application of finite element techniques to panel flutter did not appear in open literature until 1967 when Olsen[17] used a simple beam equation and quasi-steady aerodynamic pressure on two dimensional plate elements for flutter analysis of a simply supported isotropic plate. He found that extremely accurate approximations could be obtained with only a few elements. In a more recent study[18] Olsen extended his work by applying more sophisticated plate bending elements, including a 12-parameter (degrees of freedom) non-conforming model and a 16-parameter conforming model of a rectangular element as well as an 18-parameter conforming model of a triangular element. The non-conforming model provides only displacement continuity between adjacent elements whereas the conforming model provides the slope continuity also. These elements were used for the analysis of the simply supported and the clamped plates. Similar plate elements, including one model with 21-parameters,[19] were developed by many other investigators. It was found that the 18-parameter triangular element is superior, and it provided rapid convergence. The finite element technique is applicable to panels involving complicated boundary shapes and supporting conditions, cutouts, in-plane stresses and nonuniform materials which are unmanageable by the exact or Galerkin's method.

Since each element is constrained to behave in a realistic physical manner, the finite element technique requires less degrees of freedom and, hence, less computer time than the finite difference approach. However, the difficulties in generating suitable elements is a price to pay for this advantage. A large number of general purpose finite element computer programs have been generated in the past few years. Some of these programs appear applicable to panel flutter problem. A review of these programs, including the large scale NASTRAN program can be found in Reference 20.

There has been some doubt about the extent the finite element technique can be applied to solve problems considering structural and material nonlinearity (and aerodynamic nonlinearity in panel flutter problems). However, significant progress has been made recently on structural application of finite element methods to problems involving nonlinear material and nonlinear geometric behavior by approaching it in a piecewise linear fashion.[20]

3.4.3 Finite Difference

By setting up the governing differential equations in finite difference form, the procedure of solving a flutter problem becomes simpler than that of the finite element method. In addition, the former approach is applicable to nonlinear differential equations and is very versatile.[21] On the other hand, the finite difference approach may require a very large number of degrees of freedom and therefore longer computer time.

Very few panel flutter studies using the finite difference approach can be found in the open literature although this technique has been applied more often to free vibration of flat plates.[22,23] In a recent study of vibration and flutter of parallel flat plates connected by an elastic medium,[24] Johns and Taylor claimed encouraging results from finite difference solutions. They felt this method deserves further development. It is believed that this method, along with the finite element method, will be used more extensively in the future for structures with complicated configurations and support conditions.

4.0 EXPERIMENTAL CONSIDERATIONS[21,25,26]

The meagerness of meaningful experimental data compared to the large quantity of theoretical work reflects difficulties involved in performing flutter tests. There are too many factors which can significantly affect the flutter behavior of a plate structure. It is very difficult to design an experiment to cover all the important factors on the one hand and, under most circumstances, it is not an easy task to isolate the effect of a particular factor from others either. In addition, small details of model construction and test procedure are all important to final test results. Nevertheless, the most fruitful study has been a combination of theory and experiment. In order to accumulate the fundamental knowledge of panel flutter, more basic data from well-designed and well-controlled experiments have to be performed to check against the results of proposed theoretical analysis. And at present, wind tunnel testing is still the only technique beside flight test that can provide reasonable assurance of a sound panel design against flutter.

4.1 Flutter Test Techniques

The most important parameters of a wind tunnel test for panel flutter are dynamic pressure (proportional to stagnation pressure), Mach number, temperature and the pressure differential across the panel. Flutter can be initiated by varying the stagnation pressure or the Mach number. It can also be initiated by varying the pressure differential across the panel while holding other parameters constant. In addition, heating the panel at constant stagnation pressure to induce compressive thermal stessses which reduce the plate stiffness is another technique. In general, the use of a continuous flow wind tunnel is preferred over a blowdown tunnel. In the former, temperature and static pressure loading may be brought to the desired equilibrium values at each level of stagnation pressure and Mach number.

4.2 Test Model Preparation

The success of an experiment depends to a great extent on the thoroughness of the preparation before the test model is placed in the wind tunnel. This preparation includes construction of the model, measurement of model sensitivity to pressure loading and temperature differential, alleviation of cavity effect and the selection of model mounting technique and instrumentation.

Construction of a thin plate mounted on its boundary support without inducing significant stresses could be a very difficult task. Considerable effort may also be required to control and measure the sensitivity of the model to static-pressure loading and thermal stresses induced by a temperature differential between the model and its support. Dynamics of the air in an enclosed cavity behind the plate may have a significant effect in case of a shallow cavity. Two types of model mountings have been used, namely the wall mount and the use of a splitter plate (see Figure 4). From the viewpoint of easy access the former should be used although the latter has been selected more often for practical reasons. Thermocouples, pressure transducers and strain gauges are generally used to measure temperature, pressure differential across the model, plate deflection and frequency. To avoid changing plate dynamic characteristics and disturbing the aerodynamic flow, lightweight and noncontacting transducers should be used if possible.

4.3 Determination of Flutter Boundary

It is difficult to determine in an absolute sense the point at which flutter actually begins. As dynamic pressure increases small amplitude random oscillations of the panel are usually observed at pressures considerably below the flutter boundary. As the critical dynamic pressure defining the flutter boundary is exceeded, oscillation becomes heavily sinusoidal with amplitude gradually growing to the order of plate thickness. The onset of flutter can be determined experimentally within about 10% of the critical flutter dynamic pressure. In practice, a precise determination of flutter boundary is important only when the failure due to the anticipated flutter is catastrophic in nature. For the general case of flutter causing fatigue type failure, an effort to define a flutter boundary more precisely than the present experimental capability would not provide much practical usefulness.

5.0 EFFECT OF EDGE AND SUPPORT CONDITIONS

Many flutter studies on orthotropic plates conducted in the fifties and early sixties showed very large discrepancies between the results of theoretical analyses and those of experiments. One of the primary causes of these discrepancies is generally believed to be the unrealistically simple assumptions made for panel edge conditions in analysis. Recent investigations proved that the type and construction of edge support conditions have indeed a profound impact on the onset and the behavior of panel flutter.[5]

Due to the extremely hostile thermal environment during reentry, the attachment of a heat shield to the supporting substructure has been a vital concern to the design of Space Shuttle structures. In order to gain a physical insight to the significance of this problem and how attachments should be designed from the panel flutter point of view, the effects of edge and support conditions will be illustrated by presenting the results of some recent studies in this area. Effort is made to assess, separately, the influence of deflectional, rotational, torsional, and inplane constraints of panel edges as well as that of point supports.

5.1 Effect of Deflectional Spring Support

Most early analytical studies on the flutter of orthotropic panels used either simply supported or clamped boundaries that assume a zero transverse deflection at the edges. However, corrugated stiffeners may be crushed (closed end shown in Figure 5a) or left open at the edges, thus permitting deflection of those edges perpendicular to the direction of the corrugations as illustrated in Figure 5a and 5b.[12,26] The actual boundary conditions may be idealized as shown in Figure 5c with both deflectional and rotational springs. The deflectional spring could have a very small stiffness compared to the maximum bending stiffness of the panel in actual construction, and flutter could occur at a dynamic pressure far below the theoretical value obtained by the simply supported transversely unyielding assumption for the panel edges. Recent analytical and experimental studies on the effect of deflectional spring support to the flutter of rectangular orthotropic panels give the following results:

1. For panels with deflectional spring supports along edges perpendicular to the direction of maximum bending stiffness, the vibration and flutter behavior is extremely sensitive to the support flexibility.[5]

2. When the direction of air flow is perpendicular to two opposite edges on springs while the other edges are simply supported, the dynamic pressure for flutter decreases with reduction of spring stiffness. A

pressure reduction of an order of magnitude can occur for very soft springs. With air flow parallel to edges on springs a reduction of critical dynamic pressure for flutter as much as three orders of magnitude is possible as compared to those of simply supported unyielding edges. The magnitude of the reduction is significantly influenced by the twist stiffness to bending stiffness ratio of the panel and the flow angularity. The changes of flutter dynamic pressure with respect to the spring stiffness and flow angularity are illustrated in Figures 6, 7, 8 and 9.[27,28]

3. For unequal deflectional springs at edges perpendicular to the air flow, the panel would be less susceptible to flutter if the stiffer spring is located at the leading edge.[14]

4. Small details of edge conditions may induce significant changes in dynamic pressure for flutter. Even when the edge support is rigid, local distortion of the cross section at the support can introduce enough flexibility to cause substantial reduction of dynamic pressure for flutter.[29]

5. The mode of failure is influenced by the support conditions of edges perpendicular to the airflow. With corrugations open ended (see Fig. 5a) a panel begins to flutter at a very low dynamic pressure and continues to flutter for a considerable length of time before cracks appear in the skin. Even then, the integrity of the panel could still be maintained. On the other hand, a panel with crushed edges perpendicular to the airflow can withstand a much higher dynamic pressure without flutter, but when flutter does occur the failure could be quick and catastrophic.[26]

6. For panels supported by deflectional springs, analyses show that the critical flutter conditions may result from coalescense of modes other than the two lowest modes.[5]

5.2 Effect of Rotational Restraint

Significant differences in flutter boundaries have been found between plates with clamped and those with simply supported edges, i.e., edge supports with and without rotational restraint. The differences are particularly large for panels subjected to inplane compressive stresses with values close to that producing buckling.[30] The provision of rotational restraint can have a stabilizing or a destabilizing effect depending upon the supporting condition normal (transverse direction) to the plate and the extent of inplane stresses.

1. For orthotropic panels with supports transversely unyielding and elastically restrained from angular rotation at leading and trailing edges or streamwise edges, an increase of rotational stiffness would be accompanied by an increase in dynamic pressure for flutter. But this increase is only moderate in magnitude as compared to the effect of deflectional springs.[5,31,32]

2. For orthotropic panels with leading and trailing edges simply supported and streamwise edges supported by deflectional springs, rotational restraint along the streamwise edges would result in a decrease in dynamic pressure for flutter as can be seen in Figure 10. The percentage reduction would not be large for large values of deflectional spring constant but can be quite pronounced when the value of the latter is small.[5]

3. The flutter boundary of compressively stressed panels is very sensitive to rotational constraint of the panel edges. Figure 11 shows the effect of rotational constraints on all edges of an isotropic panel with transversely unyielding supports and subjected to uniform compressive stresses in both directions.[31] It can be seen that the increase of dynamic pressure for flutter with the increase of rotational restraint is completely reversed when the inplane compressive stresses become close to the buckling stress. Under these circumstances the effect of introducing rotational restraint is to lower the dynamic pressure required for flutter and the percentage reduction could be very large. It should be pointed out, however, that this analysis did not take into consideration the effect of structural damping which will be discussed later.

5.3 Effect of Inplane Restraint

The nonlinear coupling between the out-of-plane deflection and inplane membrane tensile stresses is known to be significant to the flutter behavior of plates subjected to lateral pressure loading, when the effect of finite deflection has to be accounted for. Since the nature and the distribution of these inplane stresses depend upon the degree of inplane restriction at the edges of the plate, the latter may also have considerable effect on the flutter.

In an analytical study using Von Karman's nonlinear plate equation and quasi-steady aerodynamic theory, Ventres and Dowell obtained the following results for the flutter of clamped isotropic plates with varying degree of inplane edge restraint.[32]

1. For initially unstressed plates, i.e. without lateral pressure loading, the presence or absence of inplane restraint does not affect conditions signifying the onset of flutter. This can be observed by the fact that inplane edge conditions affect only the nonlinear terms in the governing equations of motion and have a negligible effect on small amplitude motion of a flat plate. Therefore, inplane edge restraint affects the post-flutter motion only, and the amplitude of flutter motion was found to be greater for plates without inplane edge restraint.

2. Inplane edge restraint increases the stabilizing effect of the lateral pressure load for a plate with $a/b<1$, (a is plate length measured along the flow direction and b is the width of the plate) but may decrease it for plates with $a/b>1$. (See Figures 12a and 12b).

5.4 Effect of Torsional Stiffness[25,27]

Analytical results of the effect of torsional stiffness along boundaries normal to the direction of the corrugations of a stiffened panel with corrugations aligned normal to the air flow are shown in Figure 13. An increase of torsional stiffness would have no effect on the dynamic pressure for flutter when the edges are transversely unyielding, ($K_D = \infty$) but may cause an increase of critical dynamic pressure by an order of magnitude or more when the edges are supported by deflectional springs.

This analysis has been verified by an experiment in which the panel tested had corrugated doublers welded to the panel corrugations at the edges to provide torsional stiffness as shown in Figure 14. A comparison of analytical and test results is shown in Figure 15. In the absence of the doubler straps ($K_T = 0$), the panel probably would flutter at a value of the critical pressure parameter, $\lambda_{c\gamma}^*$, slightly above the theoretical curve for $C = 7$ at $K_D = 0.64$. The provision of a doubler at two edges may have increased the dynamic pressure for flutter by a factor of 30. Thus, a design that provides increased torsional stiffness at panel edges could be used to compensate for the lack of deflectional or rotational stiffness at these edges.

5.5 Plates Supported at Four Points

Thermostructural considerations suggest that a flat plate supported at several points is a possible design for the Space Shuttle heat shields. While no reference can be made to flutter analysis of panels of this type, some data on their vibrational characteristics are available.

The fundamental frequencies of isotropic rectangular plates with free edges and pinpoint supports at the four corners were first determined by Cox and Boxer[22] by applying a finite difference technique. Kirk[33] then solved the same problem by the energy method. Tso[34] later determined the fundamental frequencies of square plates supported at four points located on the diagonals of the plate and symmetrical with respect to the plate center by using the Rayleigh-Ritz method. When the results were compared with experiments, none of the nodal forms Tso assumed was satisfactory to all possible support positions. In 1969 Johns and Nagavaj[23] took both the energy approach and the finite difference approach to attack the same problem studied by Tso. They suggested that since energy methods overestimated the fundamental frequency and the finite difference method appeared to underestimate it, the latter should be preferred. In a recent review Dixon and Shore[14] compared the analytical results obtained by the finite difference method and the Lagrangian multiplier method with results obtained experimentally for an isotropic square plate. It was found that, as shown in Figure 16, the method of Lagrangian multiplier gave better agreement with experiments than the finite difference method for support positions near the plate center. They also pointed out that the magnitude of frequency is strongly affected by the support position; a maximum occurs when the supports are about halfway between the center and the edge of the plate.

Since flutter behavior is closely related to vibrational characteristics, the results discussed above imply that support positions also have a strong influence on flutter behavior. Unfortunately, the vibration studies were so limited that neither the flexibility of the supports nor the orthotropic property of the plate, which would be important for a practical design, has been taken into consideration.

6.0 EFFECT OF PANEL CONFIGURATION AND FLOW DIRECTION

The structural configuration which determines the thickness, aspect ratio, ratio of bending stiffnesses in two perpendicular directions, and the torsion-bending stiffness ratio of the plate profoundly affect flutter behavior. For orthotropic panels the flow direction with respect to the direction of maximum plate bending stiffness is also important. There are many structural configurations that can be used for a metallic heat shield panel, but those actually used for skin panels of hypersonic aerospace vehicles have been largely corrugated skin and corrugation stiffened plates. Moreover, emphasis of recent panel flutter research has been placed on the latter. Some information from recent research considered useful to the design of a heat shield panel is listed here.

1. The flutter of an orthotropic panel is strongly dependent on the flow direction. Stiffeners normal to the airstream have very little beneficial effect in preventing flutter, while those parallel to the air stream can significantly raise the dynamic pressure for flutter.[28,35]

2. For certain configurations flutter could also be a strong function of the ratio of torsional stiffness to bending stiffness of the panel. When the torsion to bending stiffness ratio, D_{12}/D_1, approaches the ratio of bending stiffness in the two principal directions, D_2/D_1, the critical dynamic pressure could be very sensitive to a small change in flow direction as shown in Figure 17.

3. The flutter boundary depends strongly on the thickness, length and the width of the panel. An increase of thickness is most effective in preventing flutter.

However, from a weight standpoint this method may not be acceptable and an application of stiffeners to change the length or the width may be more effective. For isotropic plates of the same length, the dynamic pressure for flutter in general[1,12] increases with the increase of length to width ratio. The critical dynamic pressure for a plate with length-width ratio of 10 could be two orders of magnitude higher than that with a length-width ratio of 1 for certain low values of total structural and aerodynamic damping.[36] Earlier studies indicated that for panels with a length width ratio between 1 and 4, application of stiffeners to reduce width would be effective and for panels with length-width ratio of less than 1 a reduction in length would be more effective.[2]

4. Tests on skin panels of the X-15 hypersonic aircraft indicated that unstiffened panels with low length-width ratios usually exhibited relatively large amplitude vibrations and many panels failed before flutter could be stopped. On the other hand, narrow panels exhibited mild flutter. In addition, when the corrugation-stiffened panels fluttered, the onset could be very sudden and very severe.[2]

5. Recent studies indicate that a heat shield design of corrugated panels with two edges free and the other two edges attached to deflection springs may be vulnerable to panel flutter under an estimated Space Shuttle trajectory, particularly when the direction of airstream forms a large angle with the direction of maximum panel bending stiffness as shown in Figure 18.[28]

6. Structural optimization by means of nonuniform mass distribution can lead to a weight saving of more than 15% compared to that of a corresponding uniform panel satisfying the same flutter requirement.[37,38]

7.0 EFFECT OF AERODYNAMIC HEATING

It is well known that a thermal load acting on a panel restrained at its edges can substantially reduce the rigidity of the structure, thus rendering it susceptible to vibration. There are two primary factors contributing to the apparent reduction of rigidity, namely, the introduction of in-plane thermal compressive stresses and the reduction of the modulus of elasticity at high temperatures. Numerous theoretical and experimental studies have been conducted on the effect of general inplane stresses to a thin panel including a few devoted exclusively to the effect of thermal stresses.[39,40,41] In these studies thermal stresses induced by nonuniform temperature distribution, temperature discontinuity at edge supports or uniform temperature rise of panels with edge restraints have been investigated. In all cases the magnitude of thermal stresses, and hence the effect on flutter, would be greatly influenced by the edge support conditions.

For panels subjected to a uniform temperature rise, an increase of boundary restraint which prevents thermal expansion would increase thermal stresses induced and, therefore, lower the flutter boundary. The most critical situation for flutter would be a panel under buckling stresses.[41]

Nonuniform temperature distribution may also have a significant effect on the flutter boundary even if the panel is free to expand at its boundaries. In a study of a simply supported isotropic plate with a parabolic temperature distribution, Schaeffer and Heard[39] found that self-equilibrating stresses associated with such a temperature distribution can substantially reduce the flutter boundary. For a square, simply supported aluminum panel with a length-to-thickness ratio of 300, a temperature difference of only 27°F between the center and edges of the panel would cause a 61% reduction of the dynamic pressure for flutter (a further increase of the temperature difference would cause the panel to buckle). It appears that the effect of self-equilibrating stresses caused by nonuniform temperature distribution is just as important as the uniform compressive stresses.

Sikand and Libove[40] extended the above study to investigate the effect of axial and flexural stiffness of edges as well as the temperature discontinuity at the supports for panels under sinusoidal temperature distribution. It was found, as shown in Figure 19, that substantial reduction of dynamic pressure for flutter could be caused by the presence of axial stiffeners at panel edges. Further reductions were observed when flexural stiffness is provided for the edge stiffeners and when a temperature discontinuity at edge supports exists.

These results have demonstrated the importance of thermally induced stresses to the flutter behavior of a thin plate. However, the studies are too limited in scope to draw any conclusion for a general case and the effect of aerodynamic heating on an orthotropic panel with various edge conditions applicable to Space Shuttle heat shields is yet to be reported. Furthermore, no reference can be made to the effect of reduced material modulus at high temperatures. It should be pointed out that when a panel is subjected to a thermal loading, not only is the stiffness of the panel itself reduced but also that of the boundary supports, thus compounding the effect of lowering the critical dynamic pressure for flutter. The change of modulus against temperature rise for materials applicable to Space Shuttle heat shields will be discussed in the following section.

8.0 EFFECT OF MATERIAL PROPERTIES

The rigidity of a structure is the ultimate safeguard against flutter. For the same structural weight, high rigidity can be obtained through efficient design of the structural shape and its boundary conditions or through proper choice of materials. So far as material is concerned, a higher modulus-to-density ratio, E/ρ, would correspond to a higher critical flow speed for flutter. Therefore, a comparison of this parameter for various candidate materials would be a measure of their efficiency against flutter.

The approximate values of E/ρ for several high temperature materials applicable to a radiative heat shield panel are plotted against temperature in Figure 20. It should be pointed out that these relative values do not give actual differences in stiffness of a panel. The flexture stiffness of a panel is proportional to the parameter $\frac{E}{\rho^n}$ where the value of n could be anywhere between 1 and 3, depending upon the panel configuration. For example, n=3 for an isotropic solid plate, and n approaches 1 for an idealized deep sandwich with two thin face sheets and a zero weight core structure. For a corrugation stiffened plate, n will be somewhere between 1 and 3. Therefore the differences in structural stiffness could be much larger than those shown in Figure 20.

It can be seen from the figure that so far as flutter prevention is concerned, lightweight beryllium should be the best choice for temperatures up to 1000°F.[42] Metal matrix composites such as Borsic/Ti also provide very high stiffness. For higher temperature ranges, the cobalt based Haynes 188 appears superior among super alloys, and columbium is better than TDNiC at temperatures above 1500°F.

The effect of a coating to prevent oxidation of heat shield material such as that needed for columbium[43] is quite uncertain. It is interesting to note the test results of coated columbium panels (see Figure 3) in the flutter flight experiment of the ASSET program.[3] The single face corrugation stiffened panels made of 0.0045 inch D-14 columbium foil coated with 0.0015 ± 0.0005 inch LB-2 alumnide fused slurry system (88Al-10Cr-2Si) had an initial increase in stiffness with increasing temperature as shown in Figure 21. P is the inplane tensile force acting along the direction of two free edges. The other two edges are supported. The stiffness reached a maximum at about 1400°F and then decreased with increasing temperature. It has been postulated that the increase in stiffness is caused by the closing of microcracks in the coating due to material expansion as the temperature increases. This would result in an increase of effective material thickness and, consequently, the stiffness of the section; but this theory has not been substantiated. Progress has been made recently in reducing microcracks in silicide coating on a columbium substrate through improved coating processing.[44] Also, the behavior of coated columbium in use today may be very different from that used in the ASSET program nine years ago.

No reference can be made to flutter of thin plates made of laminated fiber reinforced composite layers. The effectiveness of applying a high temperature composite as thin sheet heat shield material is quite uncertain. In such applications one would face the dilemma of using either a laminate of symmetrical layer orientations, which requires a large number of composite laminae resulting in a plate of considerable thickness, or a thin laminate of unsymmetric layer orientations which can be made with a small number of laminae. But in the latter case, coupling effect between bending and stretching[6] could significantly reduce the effective stiffness of the plate, thus canceling the weight saving potential of the composite material so far as flutter is concerned.

9.0 EFFECT OF STRUCTURAL DAMPING

The capability of a structure to dissipate vibratory energy plays an important role in establishing the level of dynamic response to excitation. Structural designers would like to understand the damping mechanism and the effect of damping on the dynamic characteristics of the structure in order to make a design which combines as many favorable damping characteristics as possible without increasing the cost and the weight.[45] Current knowledge of structural damping is far from adequate. First, the role of damping on panel flutter is not clearly understood and second, very little numerical data are available, particularly for complex built-up structures.

It is known, however, that structural damping can have a significant stabilizing effect on panel flutter, particularly for plates subjected to inplane stresses near buckling.[24] The effect obtained in analysis would depend on the type of damping model assumed. There are primarily two types of damping models: damping proportional to velocity and damping through a complex modulus modification, the [1+2g] type (this term is used to modify the elastic modulus E of the material and g is a constant determined by the elastic modulus and the viscosity of the material). The former raises the flutter boundary and experimental results indicate that structural damping can in general be described by a velocity damping whose magnitude is inversely proportional to frequency.[21] Some investigators[21,46] applying the [1+2g] type damping model have suggested that the interaction of aerodynamic damping and structural damping may cause the latter to have a destabilizing effect to a vibrating panel under certain conditions. But this destabilizing phenomenon occurs only when the aerodynamic damping is very small and when the structural damping terms involve derivatives of special coordinates. Moreover, when it occurs, it is generally very small.

It is interesting to note that improved relationships between theoretical and experimental flutter boundaries have been obtained by using [1+2g] type structural damping modeling. Shore[47] claimed recently that by incorporating such a structural damping coefficient in the bending terms of the governing differential equation, the analytical results were in reasonable agreement with those from experiments. He also suggested that g=0.01 would be a reasonable estimate for a simply supported isotropic aluminum panel. However, the appropriate value of g could not be easily estimated in general.

The effect of structural damping on the flutter boundary of an isotropic, aluminum panel subjected to inplane compressive forces is illustrated in Figure 22. The analysis was performed by using two-dimensional quasi-steady aerodynamic theory of supersonic flow. It can be seen that structural damping has a large effect in smoothing out the saw-toothed-like flutter boundary. An approximate analysis without taking damping into consideration would lead to unrealistic results.

There is evidence to suggest that dissipative mechanisms at panel supports may be the dominant form of energy loss because structures involving a large number of structural joints are more heavily damped than their single member components.[45] Some study results[47] indicate that damping at panel boundaries may increase the total structural damping by as much as five times the value representing material damping alone. However, panel flutter analysis will be much more complex when such dissipative boundary conditions are taken into consideration.

10.0 EFFECT OF OTHER FACTORS

Besides the important factors discussed in the previous sections there are other parameters which may also exert significant influence on the onset of panel flutter. The effects of some of these factors are briefly discussed here.

10.1 Effect of Elastic Coupling to Substructure

Insulation materials, when sandwiched between a heat shield panel and the substructure, may provide some elastic support to the panel. This insulation medium may even be a tough, load-bearing package which can transmit a substantial portion of the load from the heat shield to the substructure, thus resulting in a highly coupled structural system.

A few analytical and experimental studies[21,24,48,49] on the flutter of parallel plates connected by an elastic medium were limited to isotropic plates connected by linear springs with simply supported edges. It was found that elastic coupling may either increase or decrease the critical dynamic pressure for flutter depending on the stiffness of the elastic medium. Figure 23[24] shows that the flutter parameter first decreases as the stiffness parameter of the elastic medium increases, resulting in a highly destabilizing effect. After passing a critical value, further increase of the medium stiffness would cause a steep increase of the flutter parameter, thus becoming highly stabilizing.

It appears that an elastic insulation system placed directly in contact with the heat shield panel may have a large detrimental effect to the latter with regard to panel flutter. However, it is uncertain whether this will also be the case for orthotropic plates with flexible edge supports. The Langley Research Center is presently engaged in a study to obtain more information on this problem.[14]

10.2 Effect of Pressure Differential Across the Panel

To make a heat shield panel lightweight from a static point of view it is desirable to design the vehicle system in such a way that the pressure difference across the panel be minimized during boost and reentry stages. However, complete equalization is unlikely and the inplane stresses induced by this pressure differential may have a significant effect on the flutter behavior of the panel.

Since the introduction of a membrane tension on a panel stiffens the panel by stretching, a pressure differential across a flat plate would raise the flutter boundary, thus, stabilizing the panel. However, it has been found, as mentioned earlier, that this effect is sensitive to the inplane edge condition. For an isotropic flat plate with complete inplane edge restraint, the presence of a pressure differential could be slightly destabilizing for plates of certain aspect ratio.[32] An introduction of membrane compression, on the other hand, would cause the panel to be more prone to flutter. Therefore, a pressure differential across the panel of a curved plate may be stabilizing or destabilizing depending upon the direction of the pressure.

It is interesting to note the result of a nonlinear flutter analysis that, for certain isotropic panels, a pressure differential of a few hundredths of a psi may give significant changes in the flutter boundary.[8]

10.3 Effect of Boundary Layer

The presence of turbulent boundary layer is believed to be one of the primary factors causing wide disagreement between theoretical and experimental results in the low supersonic speed range.[11,50] It can cause changes in amplitude and phase relationship between pressure and wall displacement. Most of the past theoretical studies were inconclusive because of restrictions or oversimplifications imposed on the parameters used, and very few systematic experimental evaluations were designed specifically for the study of boundary layer effect.

Results of two recent experimental studies[51,52] of flat, isotropic clamped panels with length-to-width ratios of 0.5 and 2.0 indicated that a turbulent boundary layer has a large stabilizing influence on panel flutter at low supersonic speeds in the range of Mach number 1.05 to 1.40. It has a maximum effect near M=1.2 above which the stabilizing influence decreases rapidly as the Mach number increases.

In an experimental study on panel flutter of a cylindrical shell, Horn and associates[53] revealed the possibility of a highly divergent and explosive instability. They concluded that the nature of panel flutter instability is closely linked to the fluid boundary layer characteristics. A laminar or nearly laminar boundary layer profile will induce a non-destructive limited amplitude panel flutter at much lower levels of free stream energy than will a turbulent profile. However, when panel flutter does occur in the presence of a turbulent profile, it was found to be catastropic.

Since the thickness of boundary layer on part of the Space Shuttle surface would be large relative to the size of heat shield panels,[28] the effect of boundary layer on the panel flutter could be significant in the low supersonic flow range.

10.4 Effect of Curvature

The flutter behavior of isotropic plates with streamwise curvature, i.e., the axis of the curved surface perpendicular to the flow direction, has been found quite different from those with cross-stream curvature. For plates with slight streamwise curvature, earlier studies[13] predict that the effect was to lower the flutter aerodynamic pressure. The increasing curvature has a destabilizing effect up to a certain critical value beyond which the increasing curvature will have a stabilizing effect. A recent study[9] based on nonlinear analysis confirmed this prediction and found that streamwise curvature is detrimental not only in lowering the dynamic pressure for flutter but also in increasing the flutter amplitude once it begins. The flutter amplitude could be in the order of the raised height of the curve.

For plates with cross-stream curvature, past study results[21] indicate a large stabilizing effect caused by the curvature. However the stabilizing effect occurs only for panels nearly free of inplane edge restraint, and is very sensitive to the latter. For plates with completely restrained edges, cross-stream curvature would be destabilizing.

10.5 Effect of Buckling

It is well known that a plate under buckling stress is critical to panel flutter. To prevent flutter, a panel buckled by compressive stresses may require twice the thickness of an unstressed panel.[54,55] Early studies on panel flutter indicate that a buckled plate or shell may or may not be more stable than an unbuckled one, depending on edge and load conditions as well as the amplitude of the buckle. Large buckles caused by compression perpendicular to the direction of flow tend to stabilize the panel. Buckling caused by compression parallel to the direction of flow seems to be strongly destabilizing and may induce large amplitude flutter.[11]

In a recent experimental study on flutter of a cylindrical shell[53] Horn and his associates observed that a highly divergent panel flutter, occurring in the presence of a fully developed turbulent flow, was completely stabilized by buckling the shell under a combined internal pressure and axial compressive loading. A post buckling flutter occurred on a very thin shell buckled under a radial pressure loading only in the presence of a laminar boundary layer.

11.0 DESIGN OF SPACE SHUTTLE HEAT SHIELD PANELS

There are basically three major design concepts which have been seriously considered for the Space Shuttle heat shields.[56,57] They are ablative, metallic and the external insulation systems. The last two are reusable radiative types and the radiative metallic system is in a more advanced stage of development. However, the thin-sheet lightweight design may be vulnerable to panel flutter. No study on the flutter of a reusable external insulation system has been reported yet. The critical flutter condition is likely to occur during the launch phase at supersonic speed, but may also occur during reentry in the presence of severe aerodynamic heating. Since panel flutter studies have been centered on metallic panels, further discussion on heat shield design is limited to this type.

Structural configurations applicable to a radiative metallic heat shield panel include isotropic thin sheet, corrugated skin, integrally stiffened plate, corrugation stiffened plate and sandwich plate. Beside the isotropic panel, the corrugation stiffened panel has been most extensively studied. Some of the candidate designs are illustrated in Figures 24 to 28. Particular attention in the selection of these samples is paid to the edge and support conditions which are one of the most important design considerations both for aerodynamic heating and for panel flutter.

Figure 24[58] shows the edge support construction of the isotropic beryllium shingle used for heat protection on the upper cylindrical section of the Gemini spacecraft. Both inplane motion and deflectional flexibility were provided at panel edges. Similar flexible support designs for orthotropic panels proposed by the McDonnell Douglas Corporation[59,60] for a reusable reentry vehicle are shown in Figures 25 and 26. The concept of point-supported panels is shown in Figure 27, and a corrugated skin supported by clips is illustrated in Figure 28. It is noted that great emphasis has been placed on the use of corrugated skin or corrugation-stiffened plate with flexible supports for thermal stress alleviation. As discussed previously, support flexibility is detrimental from a panel flutter point of view. Whether these designs are actually vulnerable to panel flutter under Space Shuttle flight conditions and how the panel flutter consideration could be integrated into the design optimization process is an unsettled problem.

12.0 ASSESSMENT OF CURRENT TECHNOLOGY

Flight experience of hypersonic aircraft, missiles and spacecraft has revealed that flutter of lightweight outer skin panels could induce severe vibrations and, in certain cases, structural failure of these panels during supersonic flight. This problem would be compounded by the severely hostile thermal enviornment encountered in the case of the Space Shuttle. It is unclear, however, whether panel flutter will be a governing design criterion, considering all the other static and dynamic loading and life requirement of these heat shield panels.

Considerable knowledge of panel flutter has been accumulated by theoretical analysis in the past fifteen years. Although it is known that a large number of parameters can significantly affect the onset and the behavior of panel flutter, most of these analytical investigations were conducted for a specific panel configuration under a set of simplifying assumptions. The configurations were largely limited to rectangular isotropic panels with either simply supported or clamped edges. As a result, the analytical tools that were frequently applied in the past have only limited capability for solving new problems. Up to the present, analytical results are in general imprecise and can only be used as a design guide and for comparison of different designs rather than to establish a numerical flutter boundary. Only recently have orthotropic panels with discrete and flexible supports been analyzed for flutter. To handle panels of a more complex configuration and support condition, the general trend is to apply numerical techniques such as finite element or finite difference methods through computer programming. Increased use of numerical techniques should result in improvement of calculation accuracy in the near future.

The meagerness of experimental data available to substantiate the analytical techniques already developed reflects the degree of difficulty in performing meaningful laboratory tests. The many parameters that have to be considered make a realistic simulation of flight conditions impractical; and to isolate the effect of a particular factor from others is not an easy task. Nevertheless, the most fruitful studies have been a combination of theory and experiment. The effect of some important parameters has been studied and understood qualitatively, but the interaction of these parameters is poorly understood. At the present stage of technology, an accumulation of more test data is considered essential to further understand the nature of panel flutter. Wind tunnel test appears to be the only practical experimental technique short of flight test that can provide reasonable assurance against flutter for a particular panel design.

Special attention has been paid recently to orthotropic panels with flexible edge supports. It appears that, from the structural design point of view, support flexibility at panel edges would be the most important design consideration for a thin metallic heat shield panel. NASA Langley Research Center is currently engaged in comprehensive analytical and experimental studies[14,28] of the flutter of orthotropic heat shield panels with arbitrary support conditions. The analytical effort includes finite element, finite difference, Lagrangian multipliers, and normal mode analysis. The experimental effort includes fabricating and testing simple models to verify analytical techniques and to provide representative samples of actual heat shields which can provide data for candidate designs.

There are two official design criteria for panel flutter. The NASA document, Space Vehicles Design Criteria for Panel Flutter,[61] was published in 1964. Only a set of guidelines for flutter consideration in very general terms and a review of state-of-the-art on flutter analysis up to that time are included in this document. An Air Force document entitled "Design Criteria for the Prediction and Prevention of Panel Flutter"[54,55] was published in 1968. It perhaps is the most comprehensive design guide for panel flutter available today. A detailed procedure to determine the thickness requirement for panel flutter prevention was established and a comprehensive review of the literature is also included. However, several important parameters such as orthotropicity, edge support flexibility, damping and boundary layer effect were not seriously considered. As discussed previously significant progress has been made recently in these areas and although considered important to Space Shuttle heat shield design, these new developments do not appear to have yet been incorporated into the design criteria.

13.0 RECOMMENDATIONS FOR SPACE SHUTTLE PANEL FLUTTER STUDY

Current lack of confidence in ability to predict the onset of flutter indicates the need to improve the basic knowledge of the flutter of a thin panel. The basic research needed was discussed by Dowell in a recent review paper,[21] in which theoretical and experimental improvements were suggested as follows: (1) aerodynamics, particularly the effects of boundary layer and local flow; (2) structures, emphasizing nonlinear theory and panels with complex geometry; and (3) flutter prediction, for flat plates with large length-to-width ratio and the use of fully linearized potential flow theory in a nonlinear flutter analysis of curved plates and shells.

Since the Space Shuttle vehicle would be extremely weight sensitive, every effort has to be made to minimize the weight of all structural components. A comprehensive understanding of the flutter behavior of heat shield panels and other outer skin members would provide useful information not only to the detailed design of these panels, but also to the selection of the thermal protection system concept.

Technology studies that would contribute to this understanding should begin with an assessment of the extent panel flutter might dictate the design of the heat shield. Results here might well define the nature of further study needed; nevertheless, the present study has formed the basis for some suggested tasks. For example, it would be of interest to determine

1. the extent to which flutter would be a governing design criterion for a heat shield panel, considering all other static and dynamic loading imposed upon the structure from the Space Shuttle flight environment.

2. if a radiative metallic heat shield panel is necessarily more susceptible to panel flutter than other candidate heat shield concepts.

3. at what stage of flight panel flutter is most likely to occur, the location of the vehicle where heat shield panels are most vulnerable to flutter, and whether the nature of the expected flutter failure would be a fatigue type or a catastrophic type.

4. the highest surface temperature that prevailing orthotropic panel designs can resist without using flexible supports.

5. the shape effect of trapezoidal and triangular panels and the desirability of optimizing a panel design with nonuniform mass distribution.

6. the effect of a penetration caused by a foreign object such as a meteoroid.

7. the effect of thermal cycling and long time exposure to the space environment.

8. the effect of coating on a refractory metal.

9. the best structural materials from panel flutter point of view that can be used in the temperature range of the Space Shuttle surfaces, and the difference in the flutter behavior of panels made of composite materials from those of homogeneous materials.

As far as structural design is concerned, panel support appears to be the most important consideration. The effects of flexible supports and methods to improve their performance, or possibly avoid them altogether, should be subjects of concern. Studies along this line could be directed toward showing

1. how, when flexible support has to be used, the flutter characteristics of the panel might be improved.

2. how point supported panels compare with those supported at its edges.

3. the effect of flexible edge supports on curved panels.

4. the effect of the type of panel joint design including the effect of a heat leak through panel joints.

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Attachments
References
List of Symbols
Figures 1-28

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LIST OF SYMBOLS

a	Panel length in x-direction
$\overline{A_x}$	Stiffness-geometry parameter in x-direction
b	Panel width in y-direction
C	$\dfrac{D_{12}}{\sqrt{D_1 D_2}}$
D	Plate stiffness, $\dfrac{Eh^3}{12(1-\mu^2)}$
D_1	Panel bending stiffness in x-direction, $\dfrac{D_x}{1-\mu_x\mu_y}$
D_2	Panel bending stiffness in y-direction, $\dfrac{D_x}{1-\mu_x\mu_y}$
D_{12}	Panel twisting stiffness, $D_{xy} + \mu_x D_2$
D_x, D_y	Flexural stiffness in x and y directions, respectively
D_{xy}	twisting stiffness
E	modulus of elasticity
g_A	aerodynamic damping coefficient
g_B	structural bending damping coefficient
g_M	structural membrane damping coefficient
h	thickness of plate
$\overline{K}, K_D$	deflectional spring stiffness parameter, $\dfrac{k_D b^3}{\pi^3 D_2}$
K	deflectional spring stiffness parameter, $\dfrac{k_D a^3}{\pi^3 D_1}$ (Figure 9 only)
K_F	stiffness of elastic foundation

K_R	rotational spring stiffness parameter, $\frac{k_R b}{\pi D_2}$
K_T	torsional spring stiffness parameter, $\frac{K_T b^2}{\pi D_2}$
k_D, k	Deflectional spring constant
k_R	Rotational spring constant
k_T	Torsional spring constant
k_x	Nondimensional stress coefficient, $\frac{N_x b^2}{\pi^2 D_1}$
k_{xT}	Transition value of k_x producing buckling
L_G	A differential operator describing all dissipative structural terms
L_N	A differential operator describing terms involving initial in-plane loading
L_s	A differential operator describing nondissipative structural terms
M	Mach number
M_ℓ	Local mach number
m	ρh
N_x, N_{xy}, N_y	Initial inplane loadings
P	Lateral pressure load due to air flow
P_1	$\frac{\Delta pa^4}{Dh}$
ΔP	Static pressure differential
q	Free-stream dynamic pressure, $\frac{1}{2}\rho u^2$
q_ℓ	Local dynamic pressure
q_x	Rotational restraint coefficient on leading- and trailing-edge boundaries, $\frac{a\theta_x}{D_1}$

T	Temperature
T_c	Temperature at center of the plate
W	Lateral panel deflection
U	Free stream air velocity
β	$(M^2-1)^{1/2}$
γ_a	A gas constant for air
Θ_x	Rotational spring constant at edges x=0, and x=a
θ_y	Rotational spring constant at edges y=0, and y=b
λ	Flutter parameter, $\frac{2qb^3}{D_1}$
λ_{cr}	Critical flutter parameter
Λ	Flow angle
μ_x, μ_y	Poisson's ratio in x and y direction, respectively
ρ	Density of material
ω	Fundamental frequency

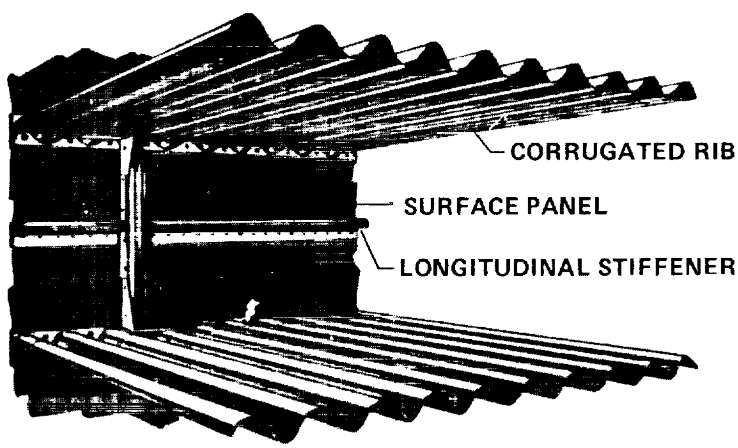


FIGURE 1 - INTERNAL VIEW OF X-15 VERTICAL-TAIL STRUCTURE

(TAKEN FROM REF. 1)

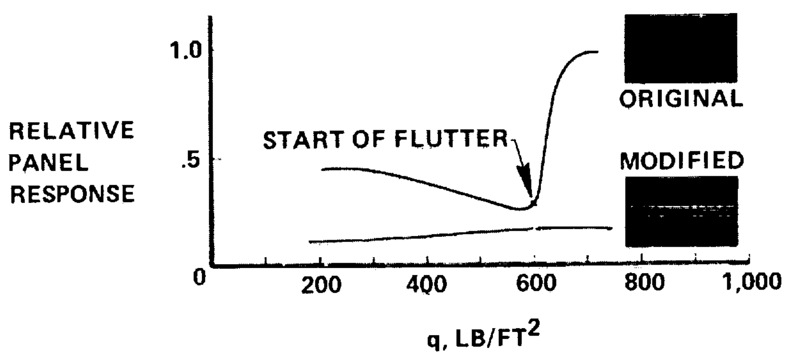
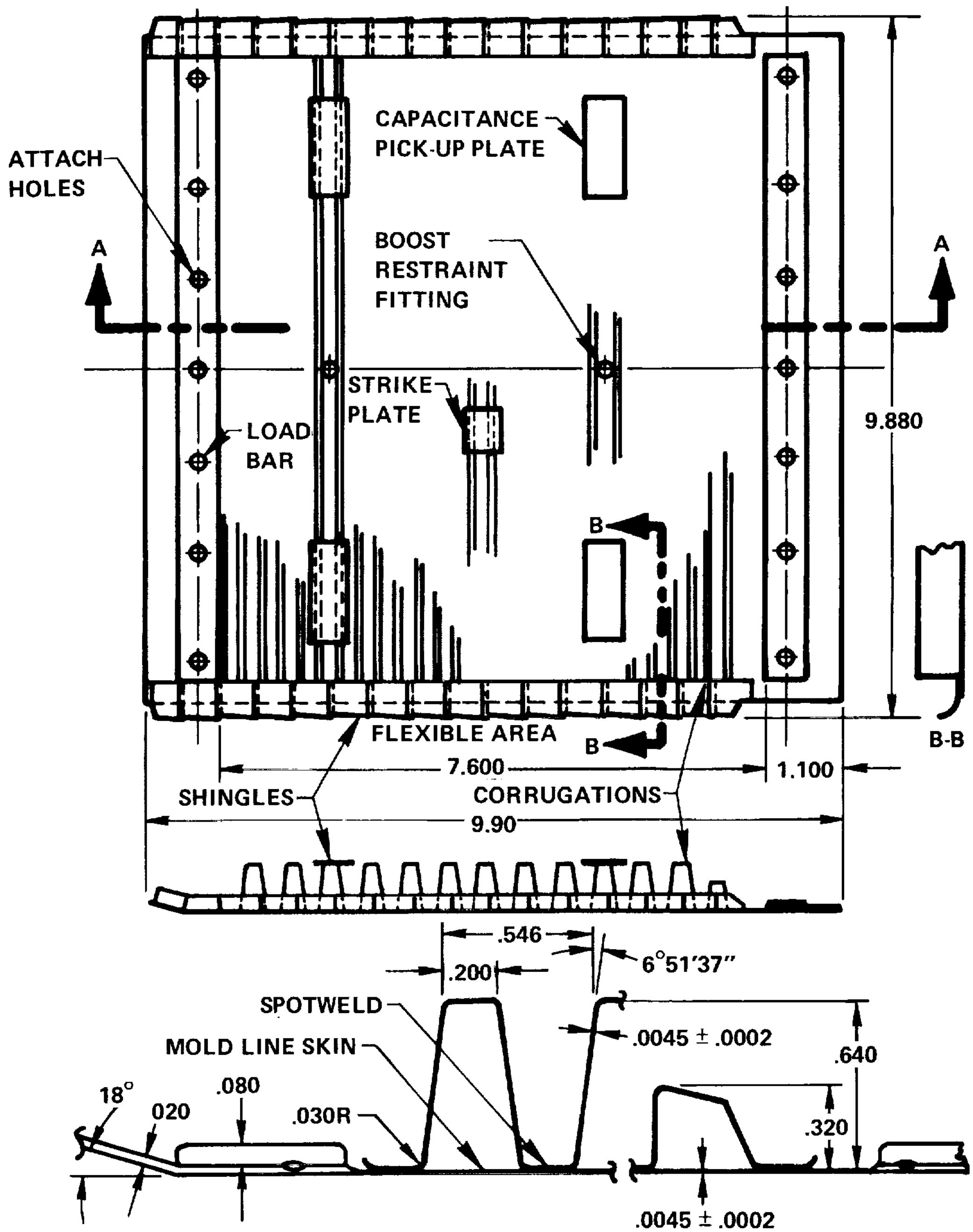


FIGURE 2 - VARIATION OF PANEL-RESPONSE ENVELOPE WITH DYNAMIC PRESSURE FROM FLIGHT MEASUREMENTS ON AN X-15 SIDE-FAIRING PANEL

(TAKEN FROM REF. 1)



SECTION A-A

(ALL DIMENSIONS ARE INCHES) (NOT TO SCALE)

FIGURE 3 - TYPICAL ASSET FLUTTER PANEL CONSTRUCTION

(TAKEN FROM REF. 3)

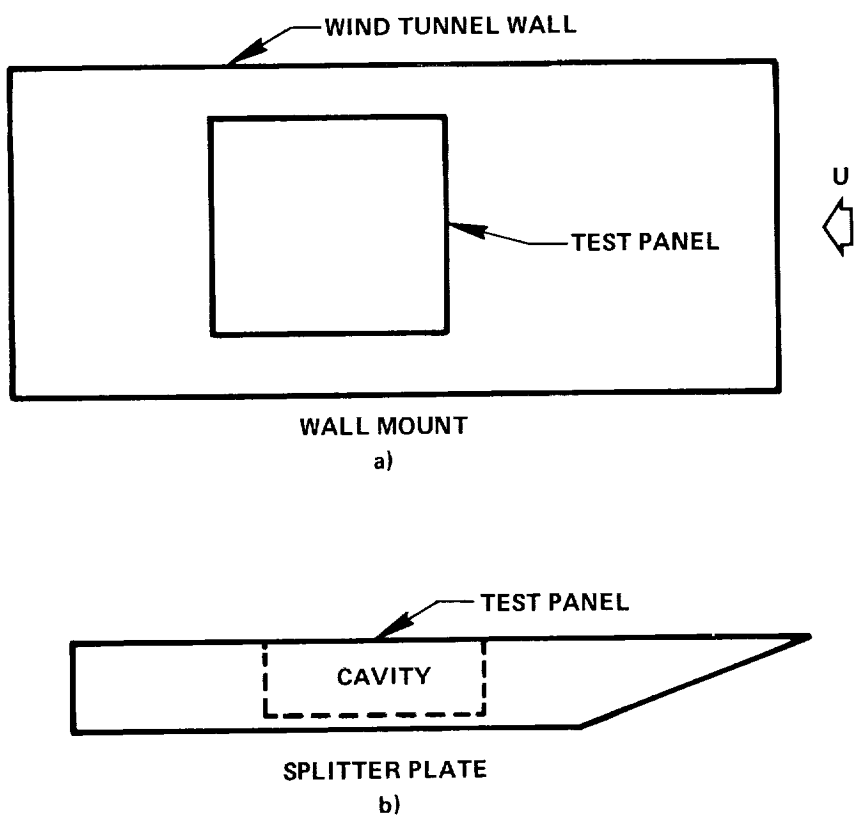
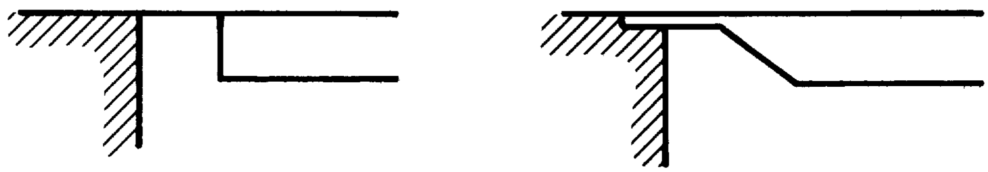


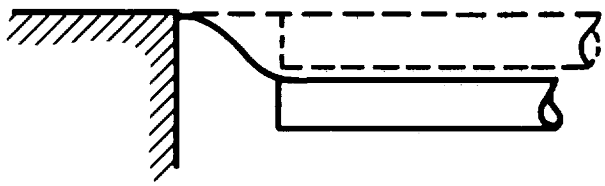
FIGURE 4 - WALL MOUNT AND SPLITTER PLATE

(TAKEN FROM REF. 21)

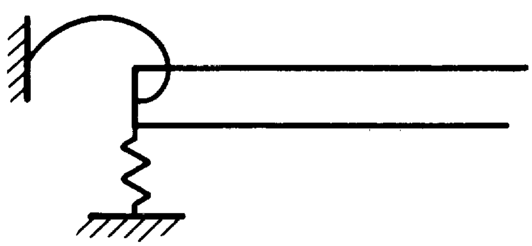


OPEN END CLOSED END

a) EDGE ATTACHMENT OF CORRUGATION-STIFFENED PANELS



b) DEFLECTIONAL BEHAVIOR OF OPEN END ATTACHMENT



c) GENERAL CASE

FIGURE 5 - BOUNDARY-CONDITION IDEALIZATION

(TAKEN FROM REFS. 12 & 26)

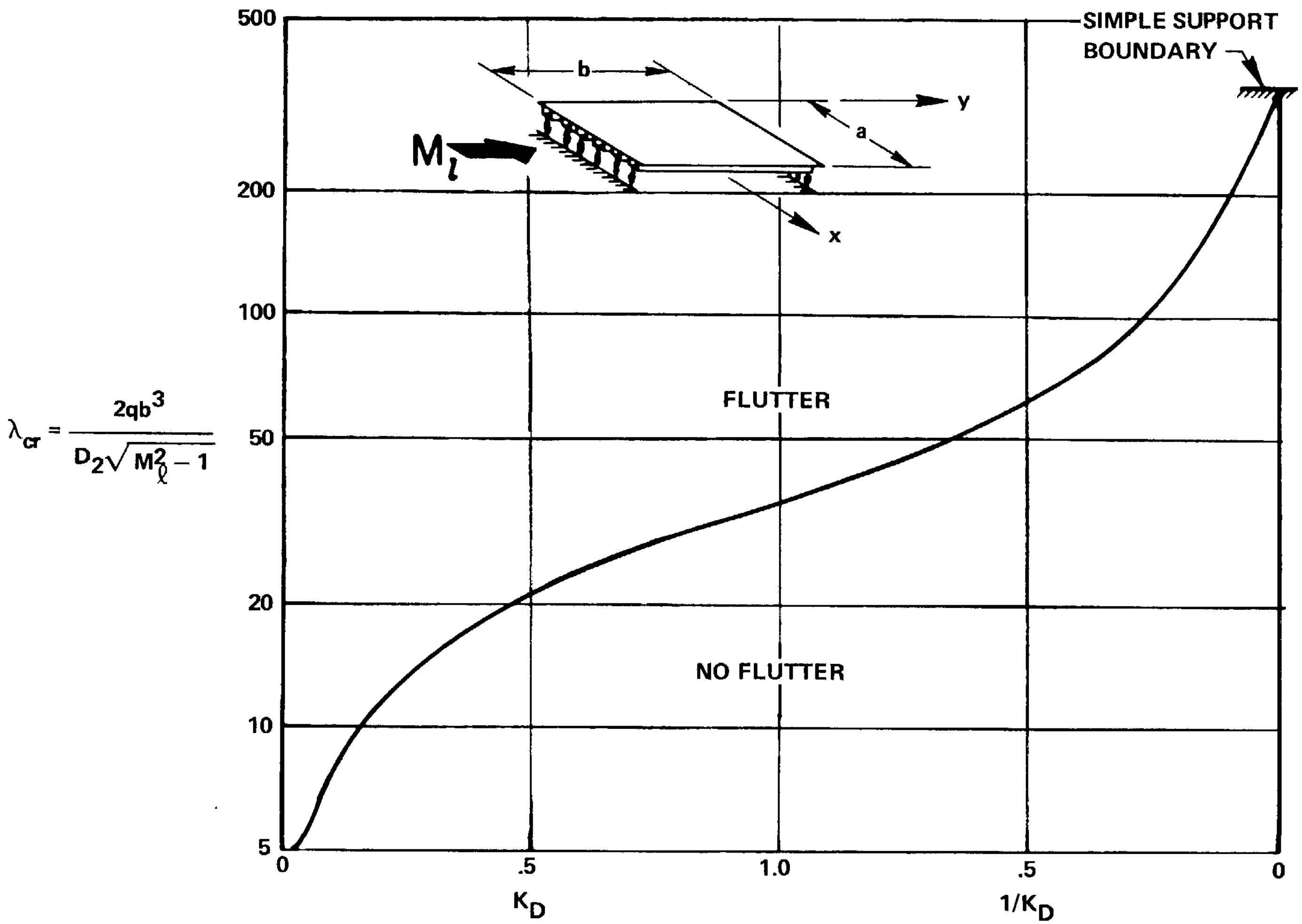


FIGURE 6 - MINIMUM FLUTTER BOUNDARY FOR HIGHLY ORTHOTROPIC PANELS WITH FLOW IN STRONG DIRECTION

(TAKEN FROM REF. 27)

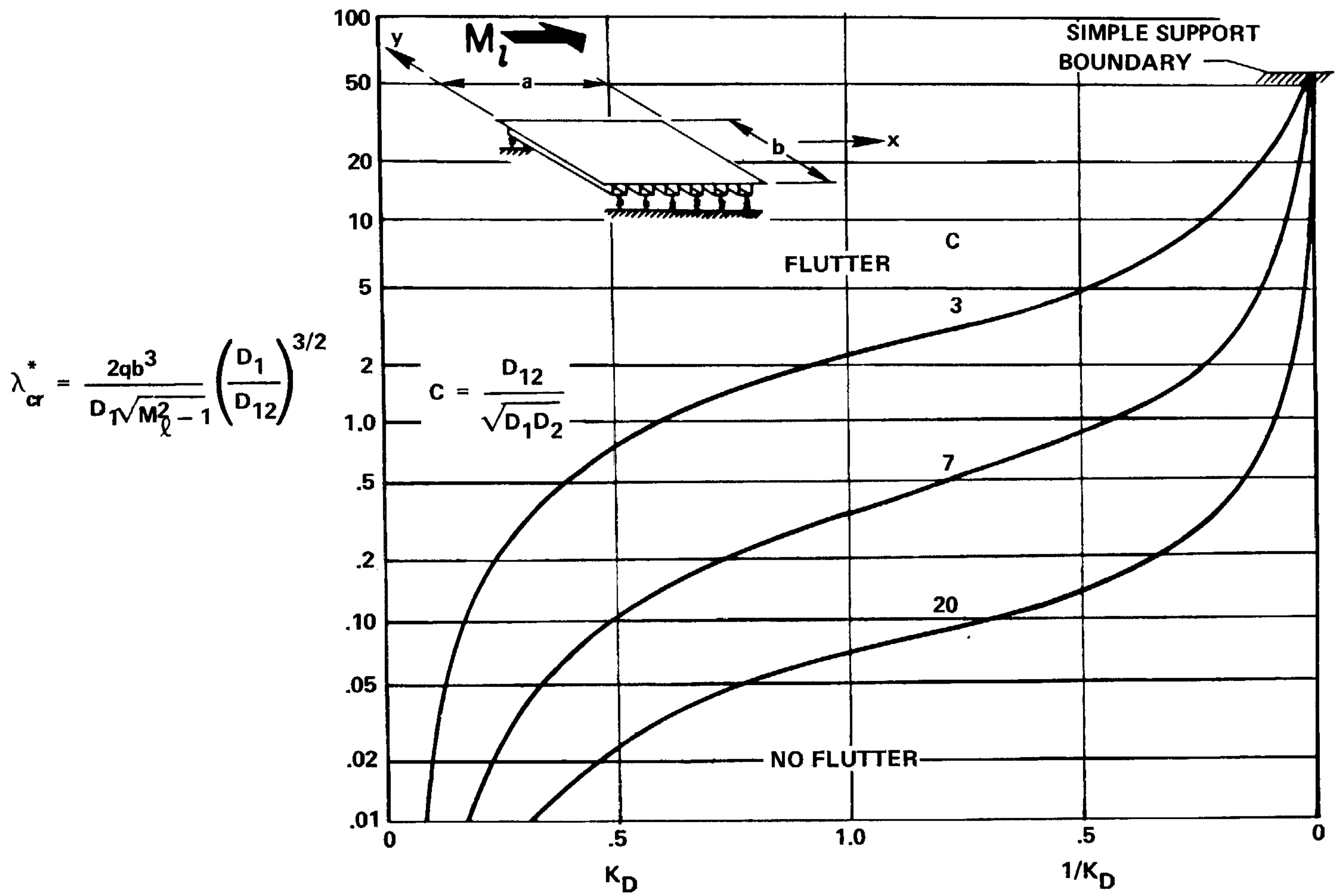


FIGURE 7 - MINIMUM FLUTTER BOUNDARY FOR HIGHLY ORTHOTROPIC PANELS WITH FLOW IN WEAK DIRECTION

(TAKEN FROM REF. 27)

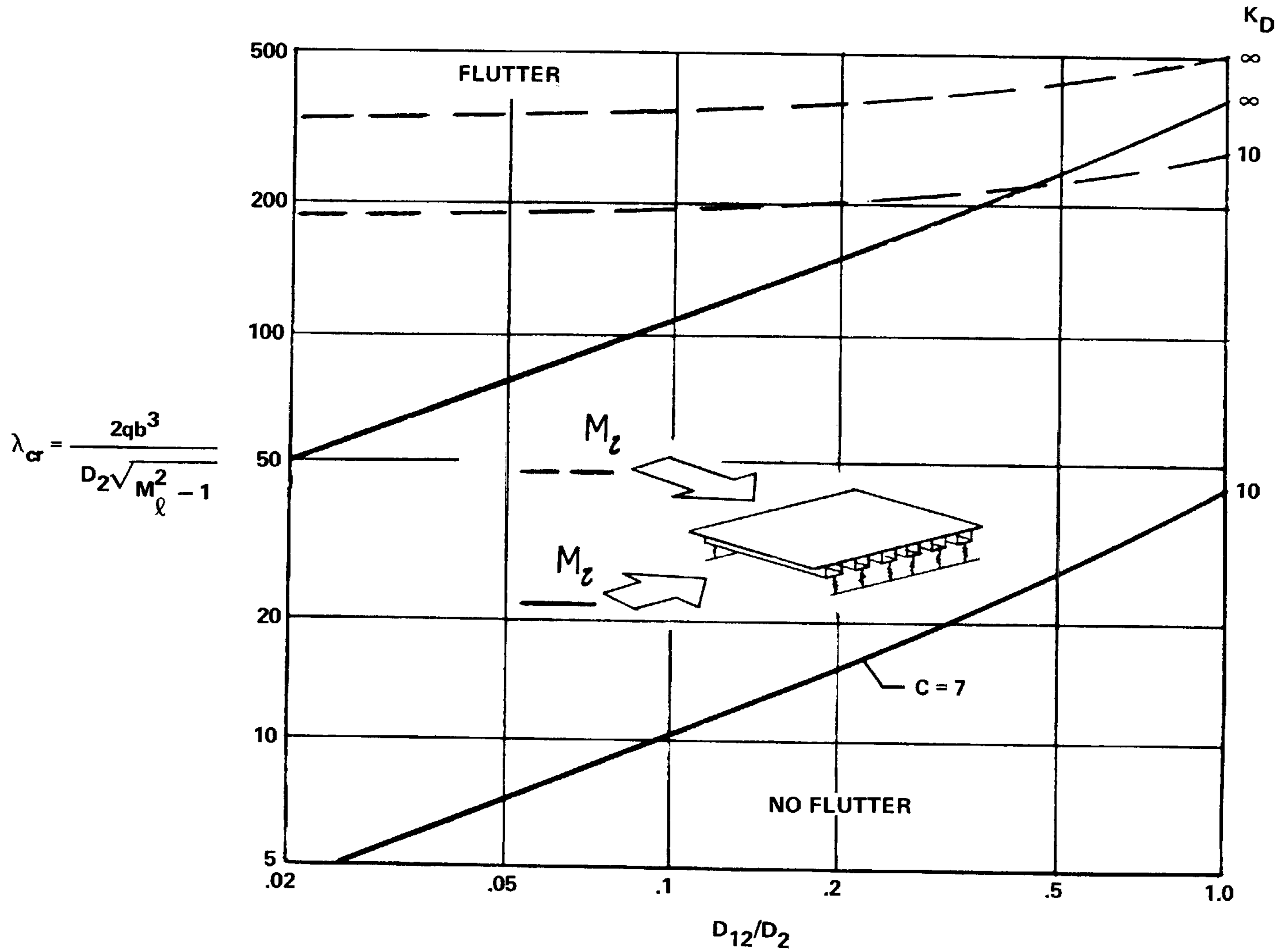


FIGURE 8 - EFFECT OF PANEL ORIENTATION ON FLUTTER BOUNDARY. $\frac{a}{b} = 1.$

(TAKEN FROM REF. 27)

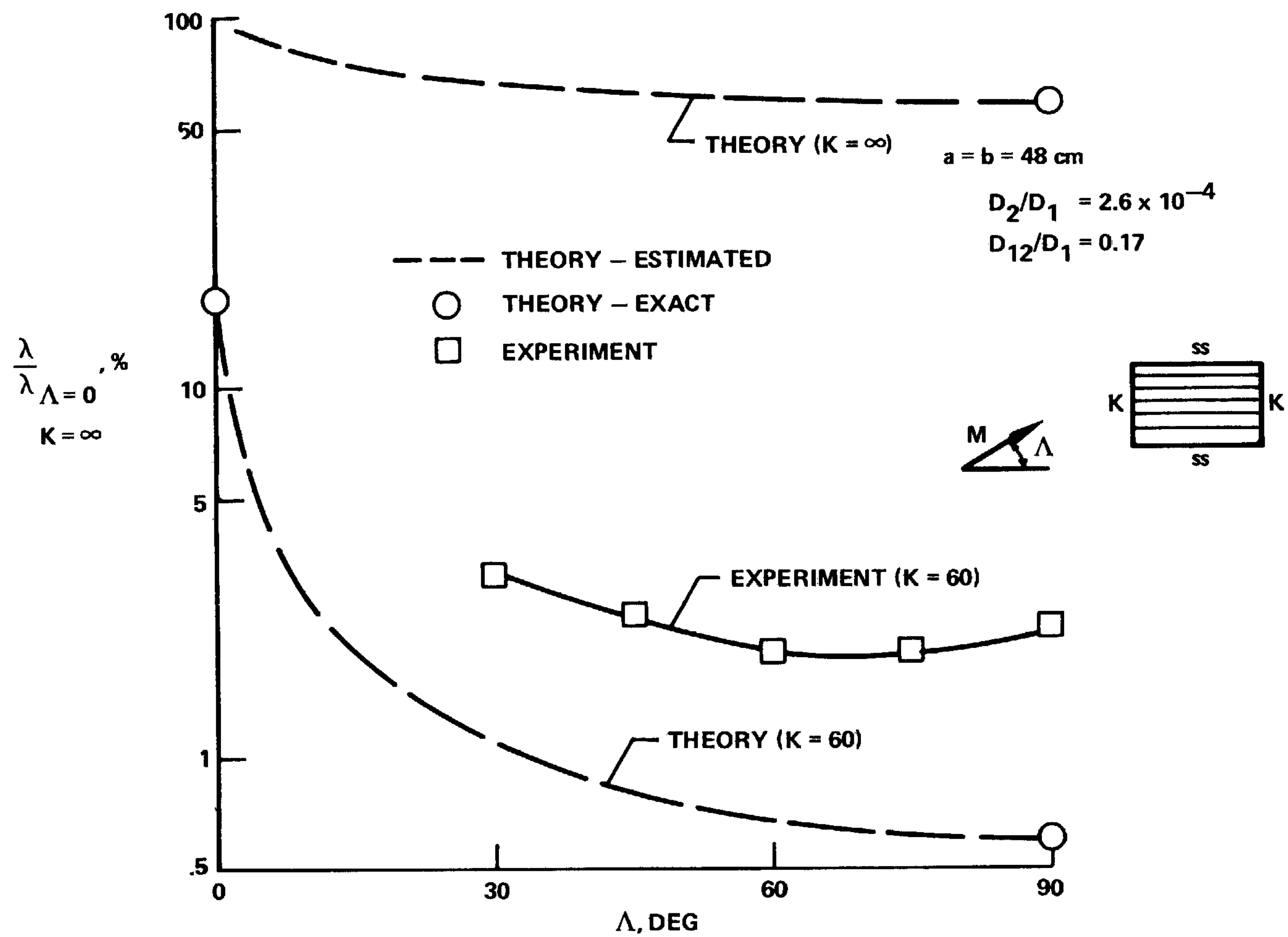


FIGURE 9 - EFFECT OF FLOW ANGULARITY ON FLUTTER BOUNDARY

(TAKEN FROM REF. 28)

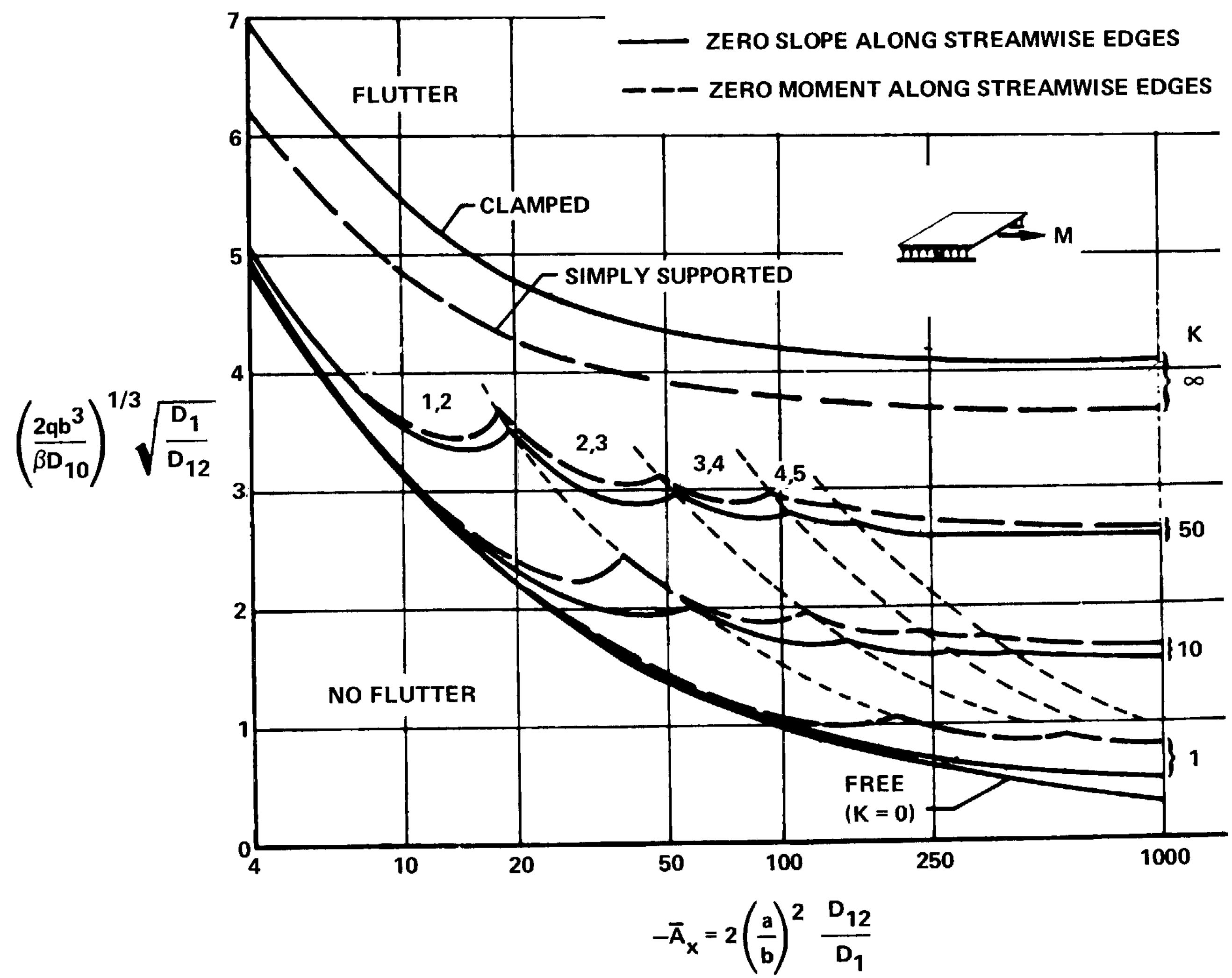


FIGURE 10 - COMPARISON OF FLUTTER BOUNDARIES FOR ZERO MOMENT AND ZERO SLOPE ALONG STREAMWISE EDGES. LEADING AND TRAILING EDGES SIMPLY SUPPORTED AND C = 7.07

(TAKEN FROM REF. 5)

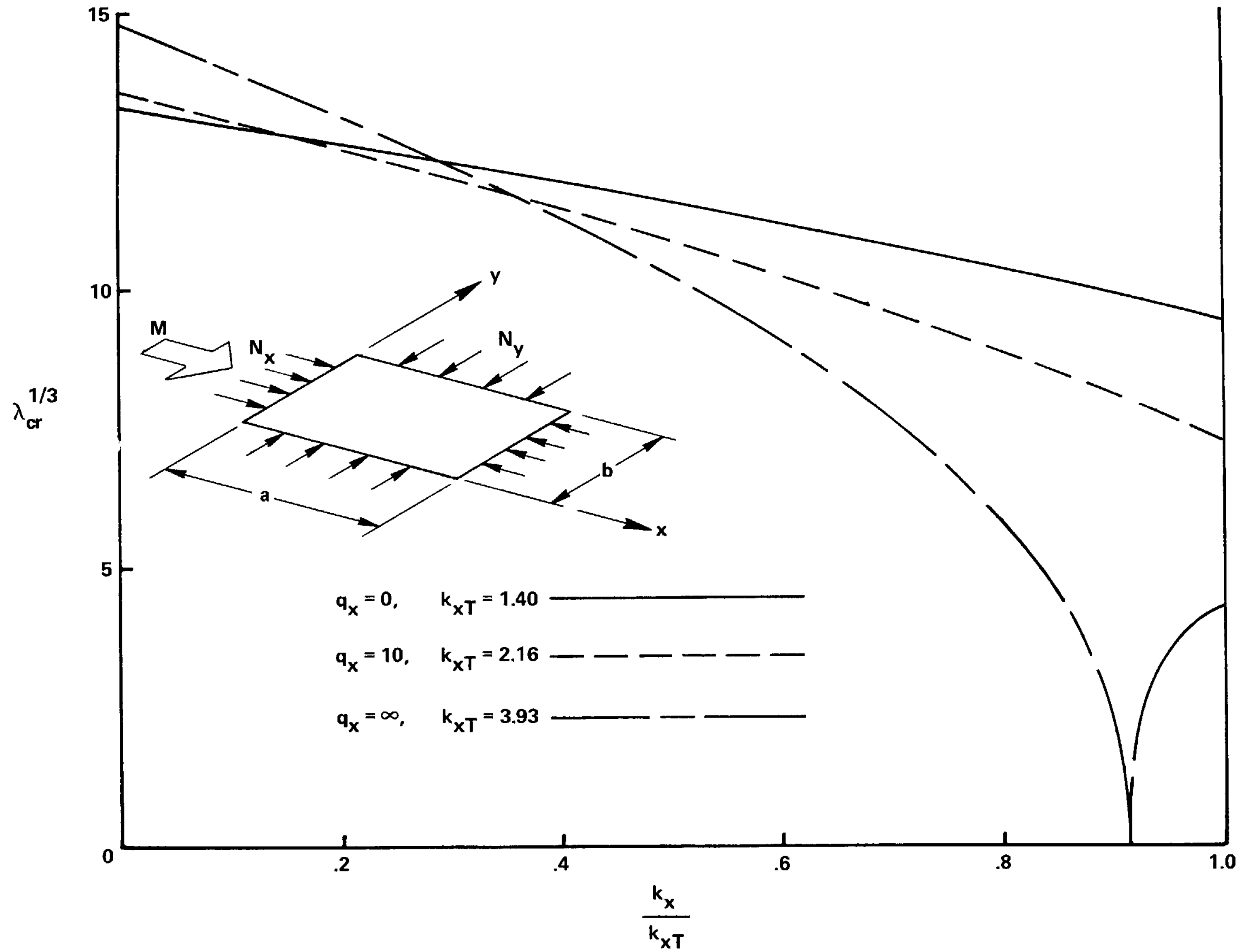


FIGURE 11 - VARIATION IN λ_{cr} WITH STRESS RATIO FOR DIFFERENT BOUNDARY CONDITIONS.
$a/b = 3; N_y/N_x = 1; \theta_y/\theta_x = 1; D_1 = D_{12} = D_2$

(TAKEN FROM REF. 31)

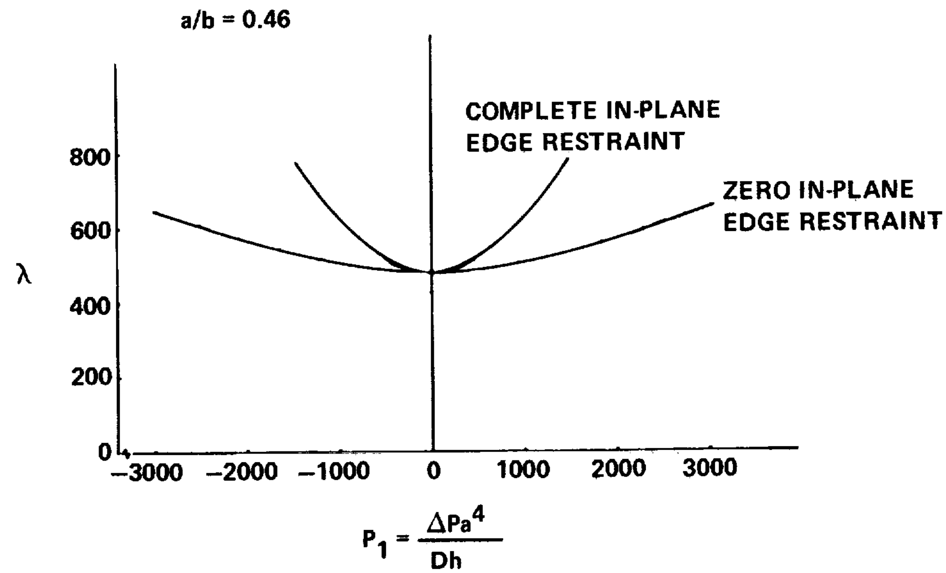


FIGURE 12a - FLUTTER DYNAMIC PRESSURE VS STATIC PRESSURE DIFFERENTIAL

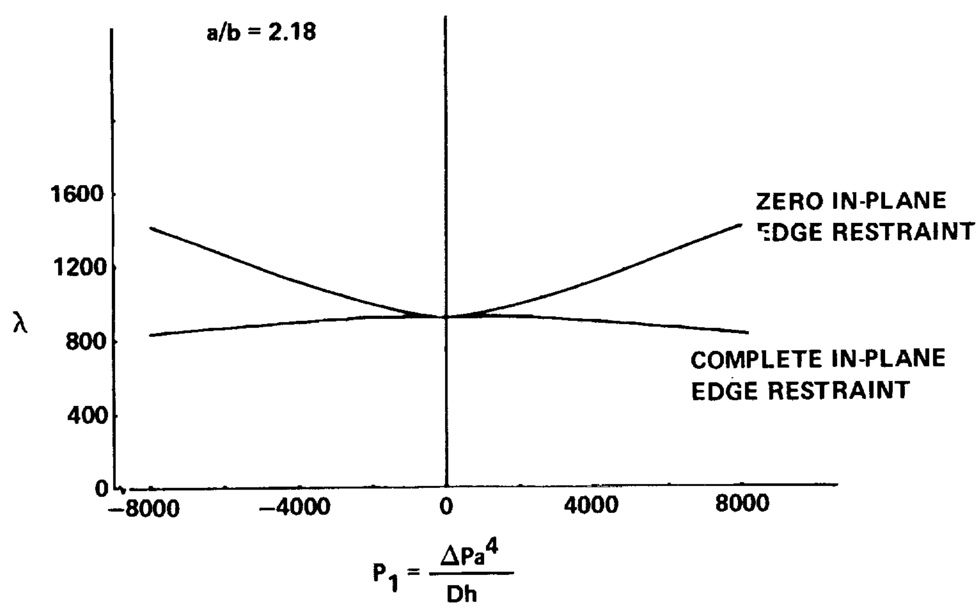


FIGURE 12b - FLUTTER DYNAMIC PRESSURE VS STATIC PRESSURE DIFFERENTIAL

(TAKEN FROM REF. 32)

20

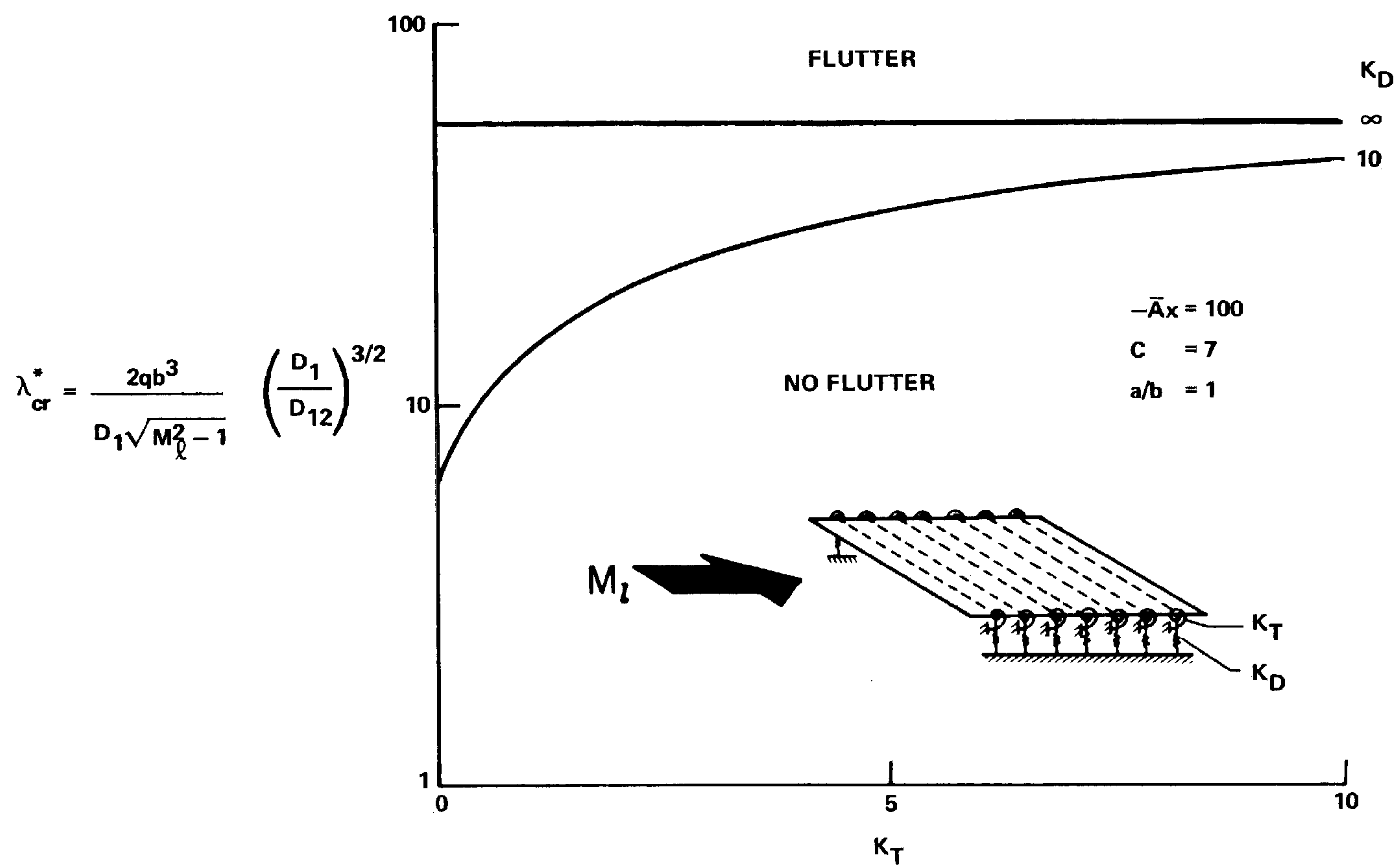
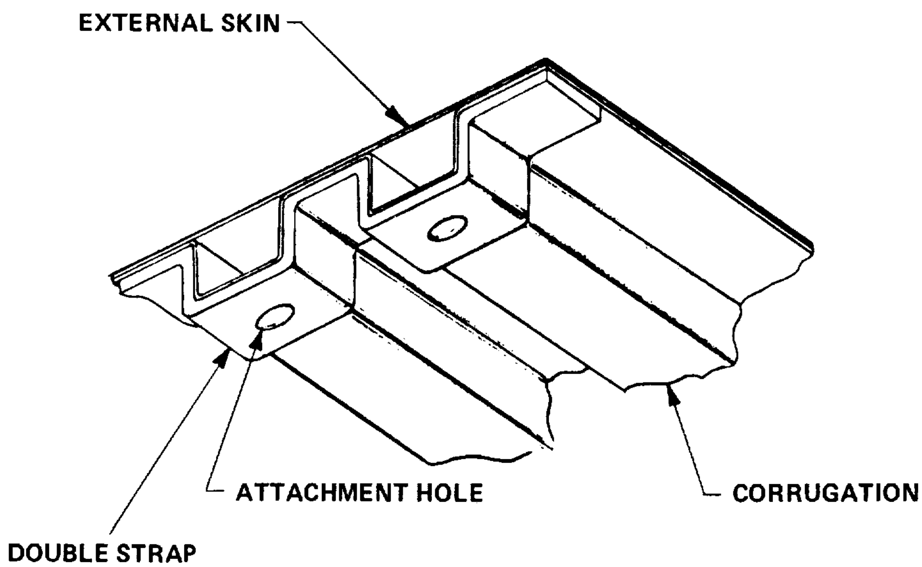
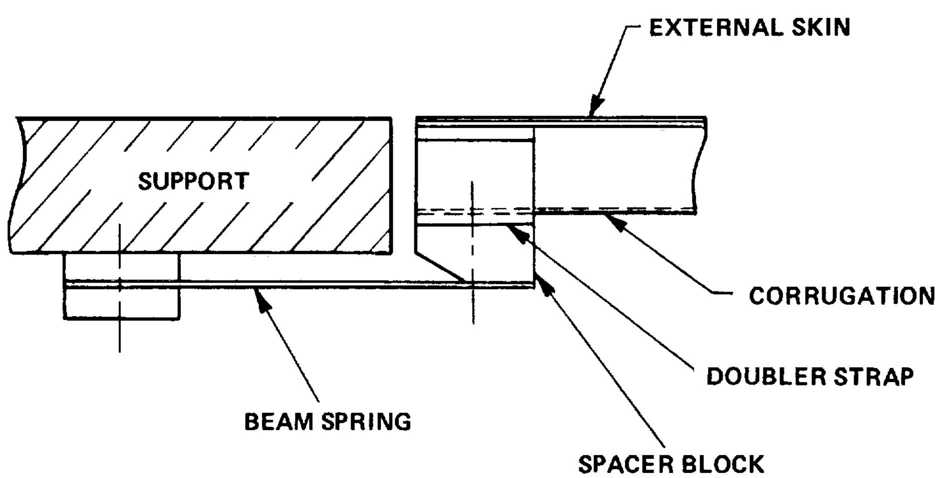


FIGURE 13 - EFFECT OF EDGE TORSIONAL STIFFNESS ON FLUTTER

(TAKEN FROM REF. 27)



a) TORSIONALLY STIFFENED EDGE



(b) BEAM SUPPORT DETAILS

FIGURE 14 - BEAM-SUPPORTED CORRUGATION-STIFFENED PANEL WITH TORSIONALLY STIFFENED EDGE

(TAKEN FROM REF. 27)

$$\lambda^*_{cr} = \frac{2qb^3}{D_1\sqrt{M_\ell^2 - 1}} \left(\frac{D_1}{D_{12}}\right)^{3/2}$$

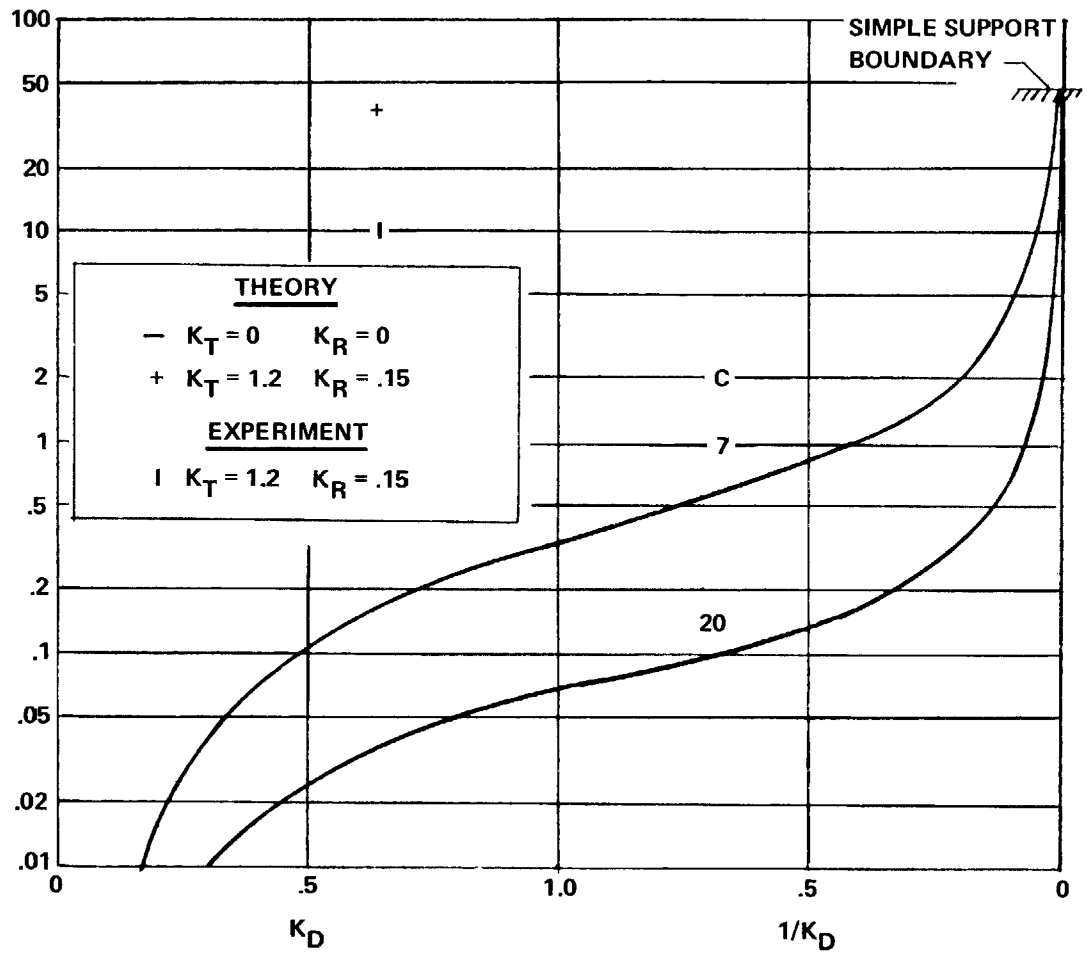


FIGURE 15 - COMPARISON OF THEORY AND EXPERIMENT FOR FLUTTER OF TORSIONAL RESTRAINED PANEL. C = 6.1

(TAKEN FROM REF. 27)

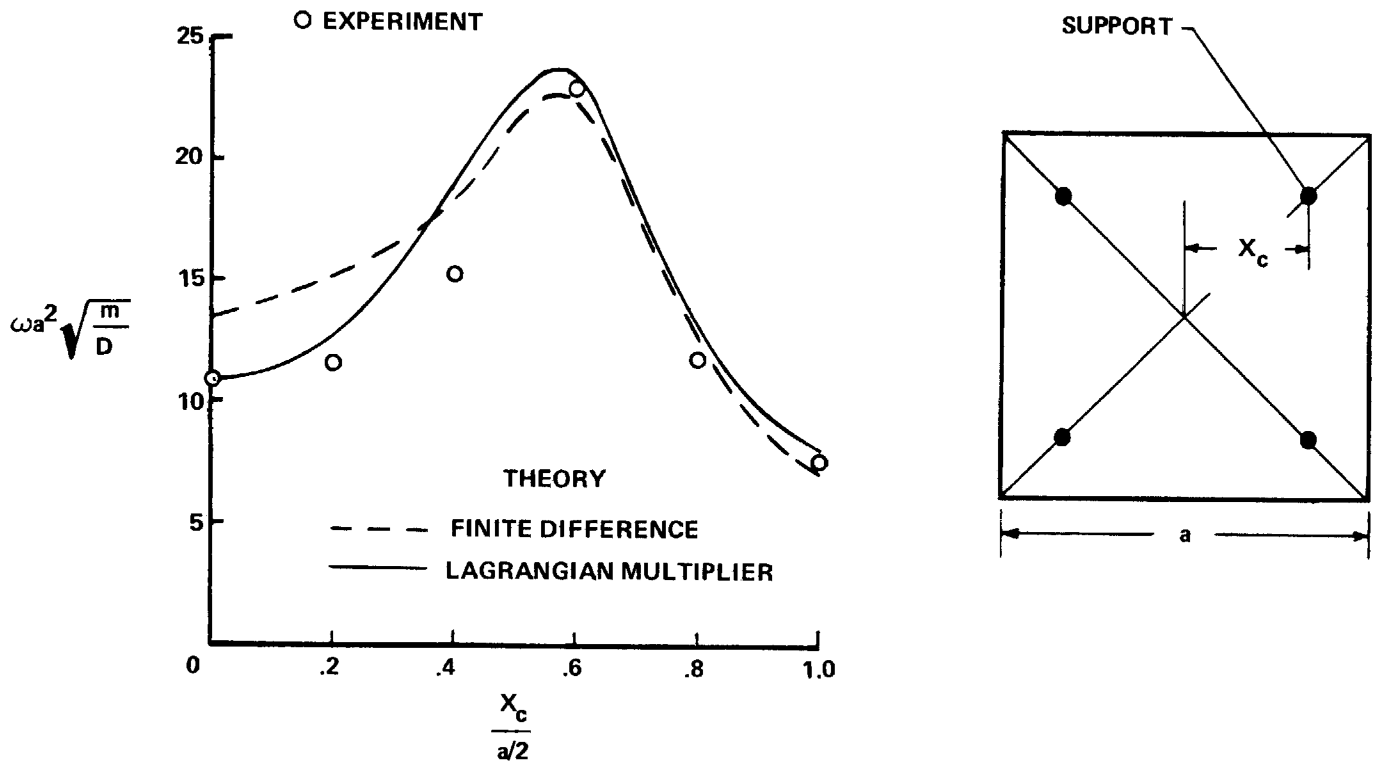


FIGURE 16 - EFFECTS OF SUPPORT POSITION ON FUNDAMENTAL FREQUENCY OF A SQUARE PLATE

(TAKEN FROM REF. 14)

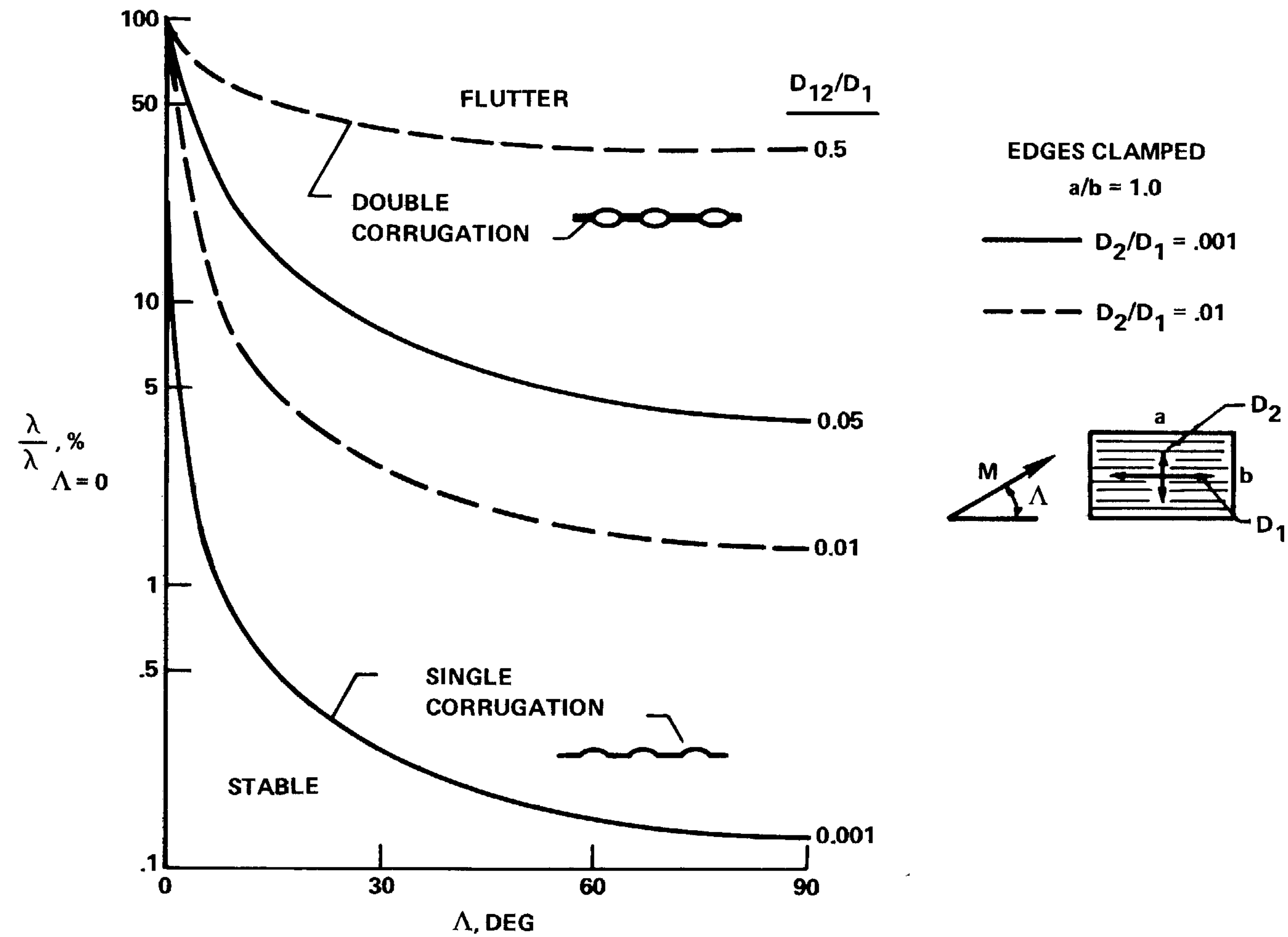


FIGURE 17 - INFLUENCE OF FLOW ANGULARITY ON FLUTTER

(TAKEN FROM REF. 28)

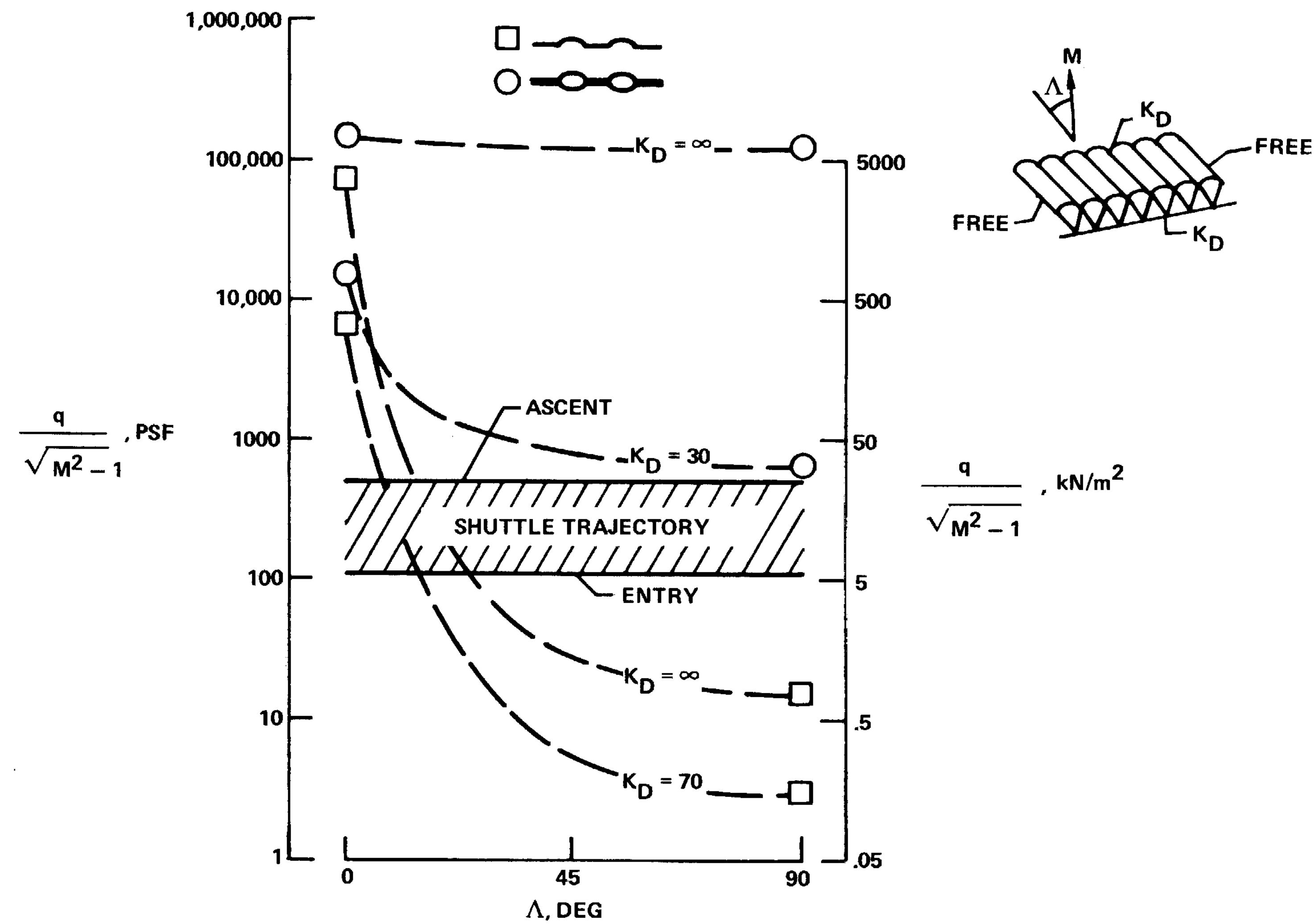


FIGURE 18 - FLUTTER COMPARISON OF SHUTTLE SURFACE STRUCTURE
PANEL SIZE: 36 cm x 107 cm

(TAKEN FROM REF. 28)

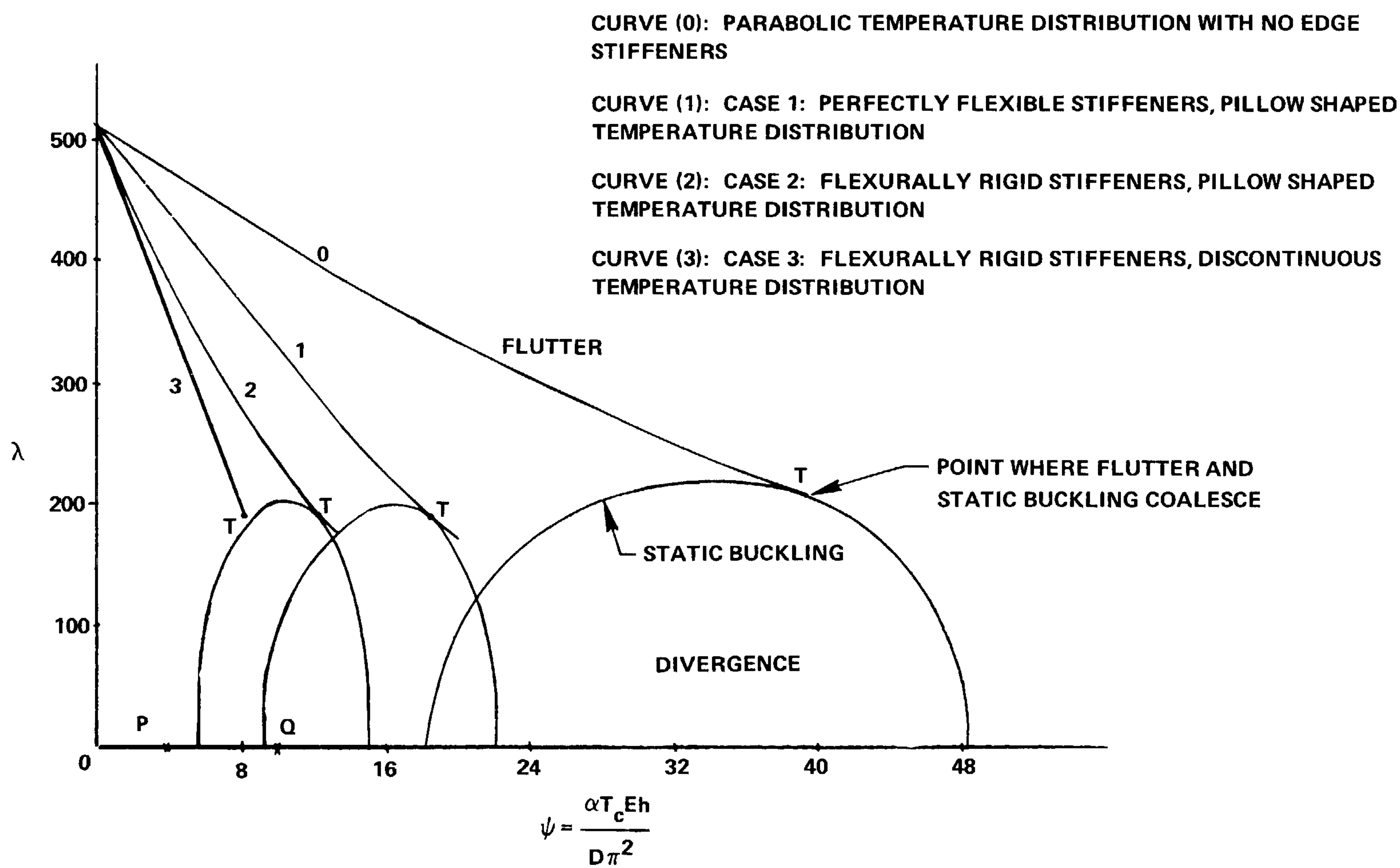


FIGURE 19 - FLUTTER COMPARISON OF THERMALLY STRESSED FLAT PLATES WITH DIFFERENT COMBINATIONS OF EDGE STIFFENERS AND TEMPERATURE DISTRIBUTION

(TAKEN FROM REFERENCE 40)

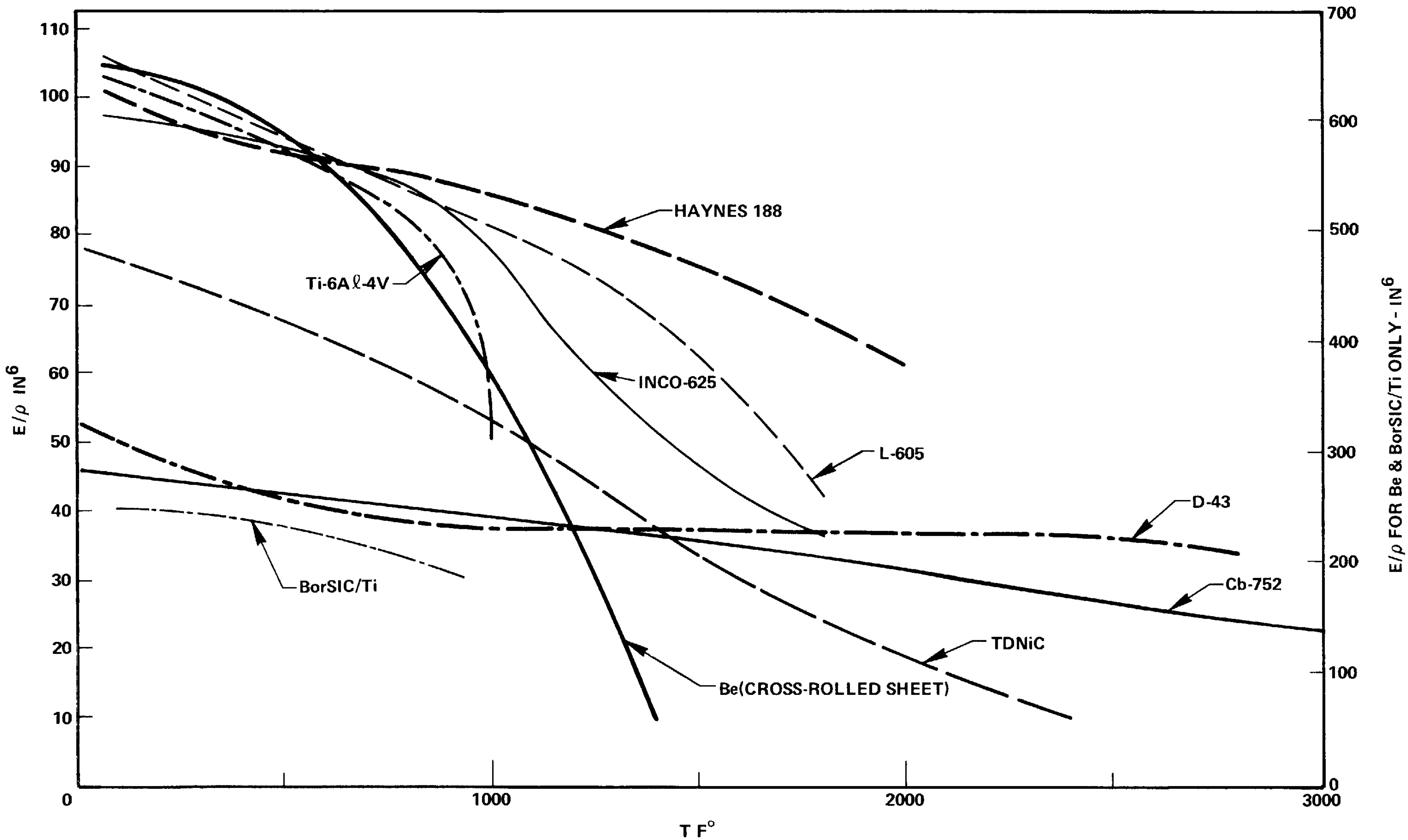


FIGURE 20 - MODULUS-TO-DENSITY RATIO OF CANDIDATE HEAT SHIELD MATERIALS

EFFECTIVE STIFFNESS INCREASE AS A FUNCTION OF TEMPERATURE

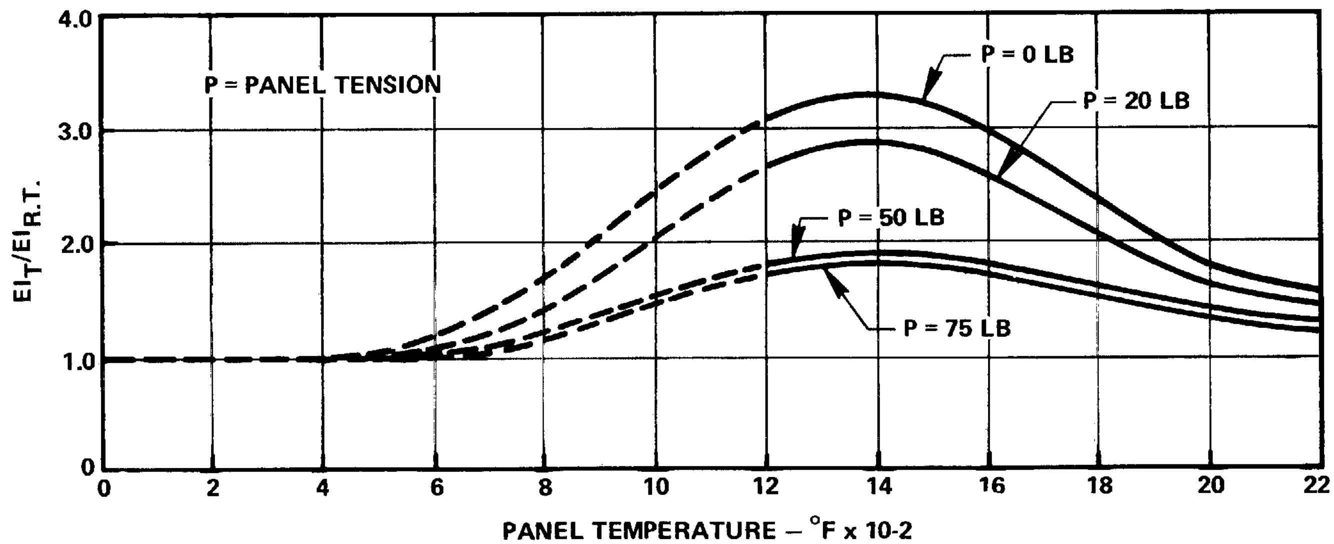


FIGURE 21 - FLUTTER PANEL EXPERIMENT OF ASSET PROGRAM

(TAKEN FROM REF. 4)

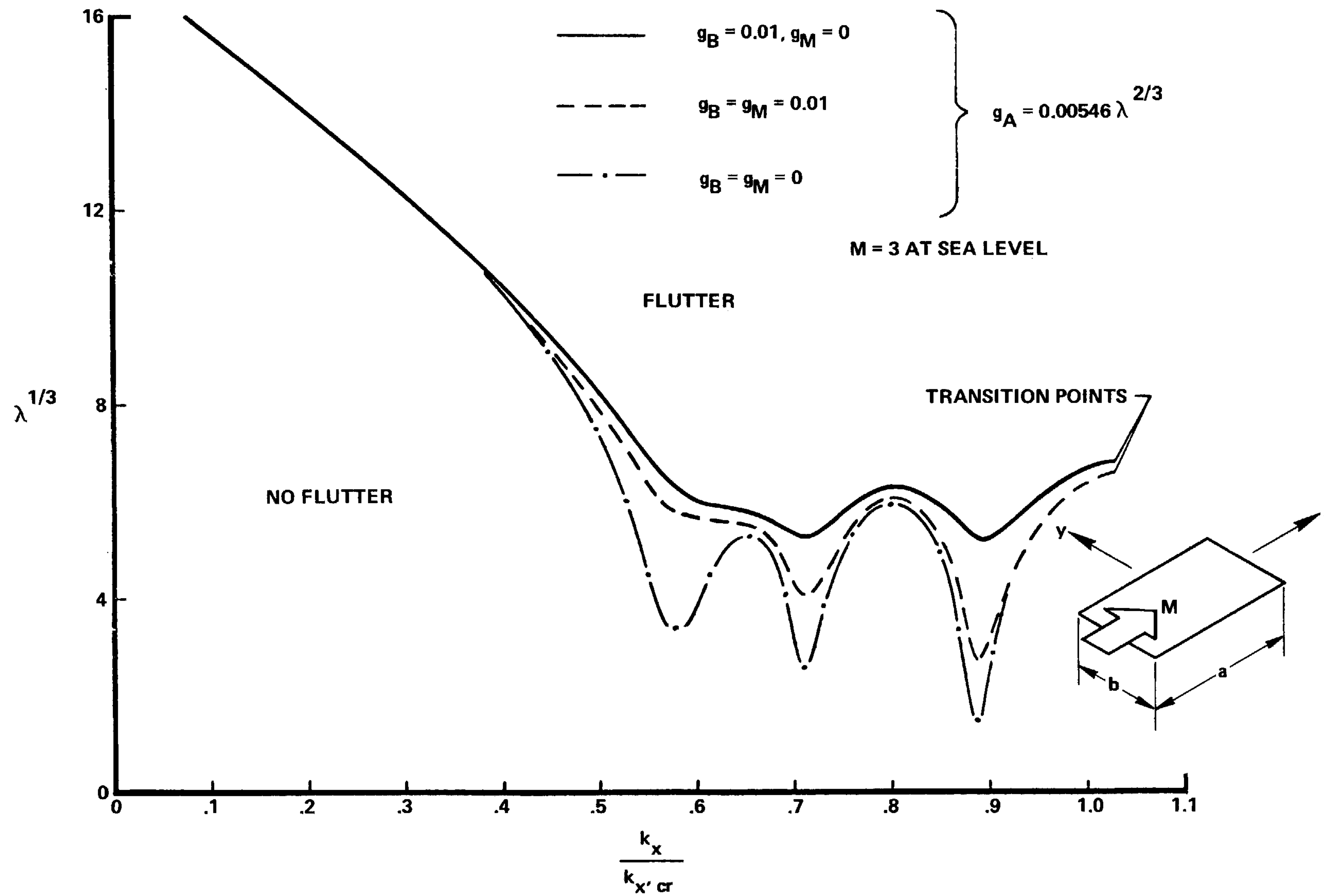


FIGURE 22 - EFFECTS OF STRUCTURAL DAMPING ON THE FLUTTER BOUNDARY FOR A SIMPLY SUPPORTED ALUMINUM-ALLOY PANEL AT SEA LEVEL. M = 3.0; a/b = 4.0; $N_y/N_x = 0$

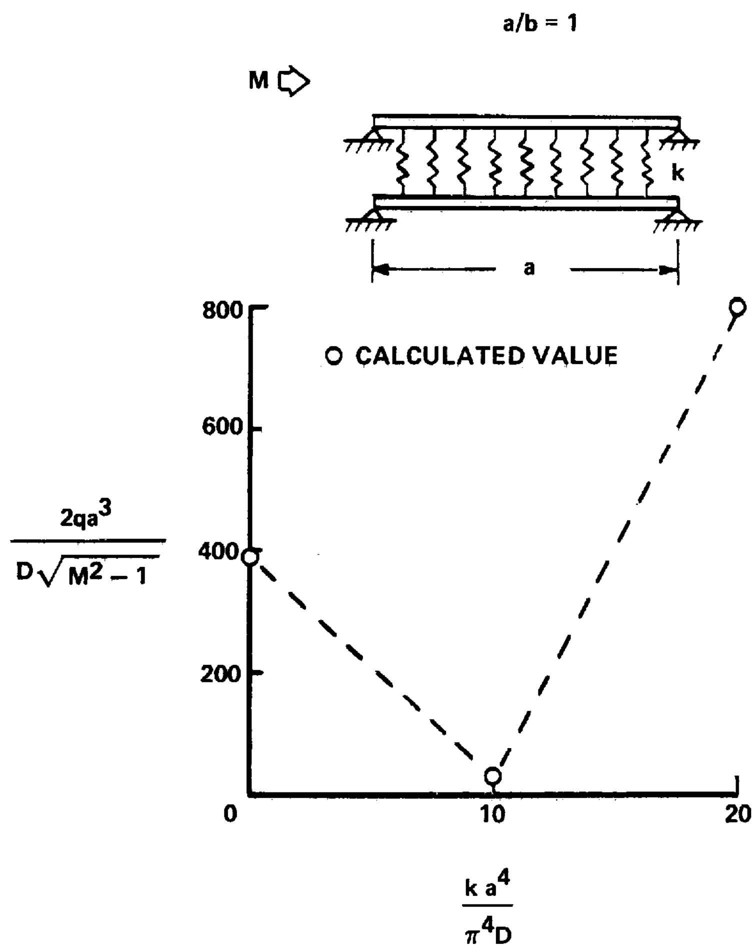


FIGURE 23 - EFFECT OF ELASTIC COUPLING TO ELASTIC SUBSTRUCTURE

(TAKEN FROM REF. 14)

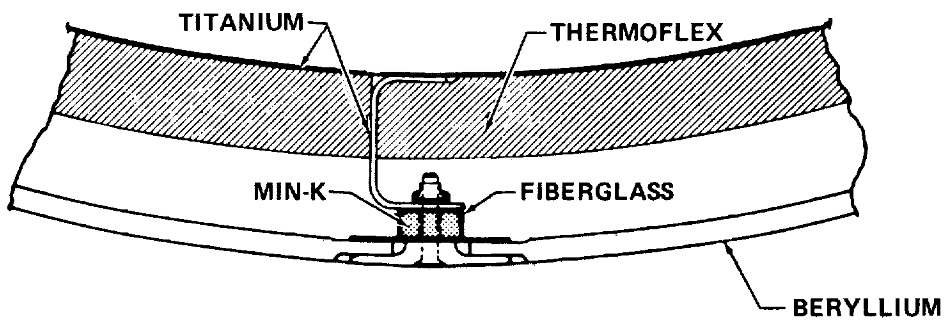


FIGURE 24 - THERMAL PROTECTION SYSTEM ON THE UPPER CYLINDRICAL SECTION OF GEMINI SPACECRAFT

(TAKEN FROM REF. 58)

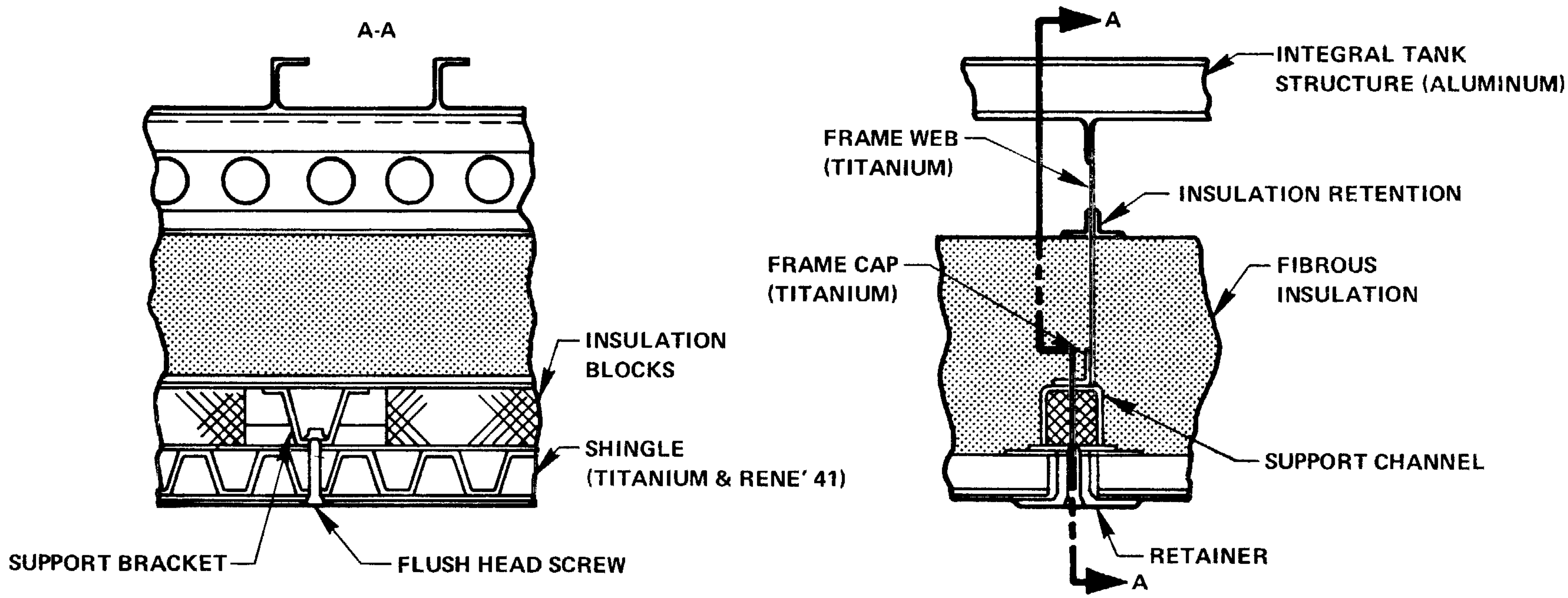


FIGURE 25 - METALLIC SHINGLE THERMAL PROTECTION SYSTEM FOR AN INTEGRAL LAUNCH AND REENTRY VEHICLE SYSTEM

(TAKEN FROM REF. 59)

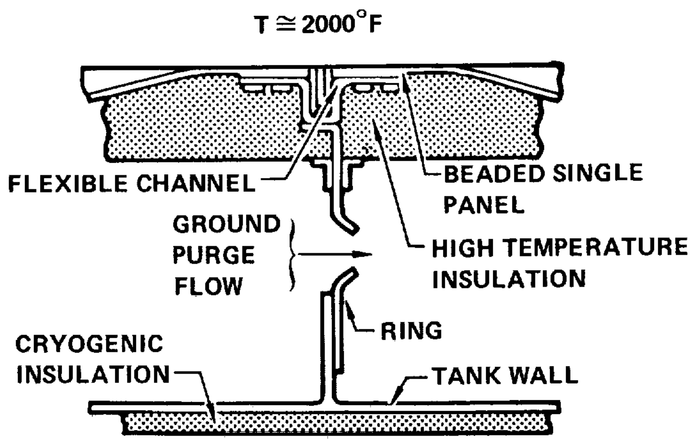


FIGURE 26 - JOINT AND EDGE SUPPORT DESIGN OF SPACE SHUTTLE TPS

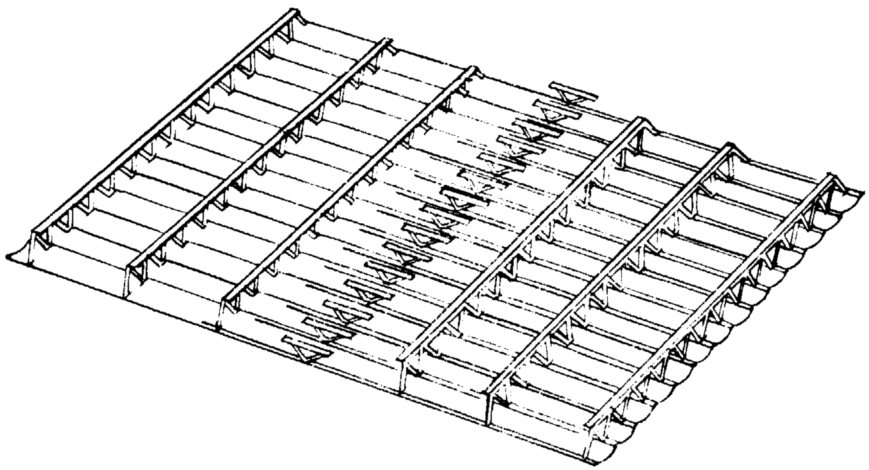
(TAKEN FROM REF. 60)

HAT STIFFENED CORRUGATED SKIN

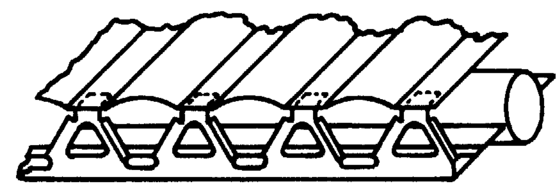
DIMPLED OR SANDWICH CONSTRUCTION

FIGURE 27 - HEAT SHIELD CONFIGURATIONS WITH POINT SUPPORTS

(TAKEN FROM REF. 14)



CORRUGATED SKIN WITH MULTIPLE SUPPORTS



THERMAL EXPANSION JOINTS

FIGURE 28 - HEAT SHIELD WITH MULTIPLE DISCRETE SUPPORTS

(TAKEN FROM REF. 14)